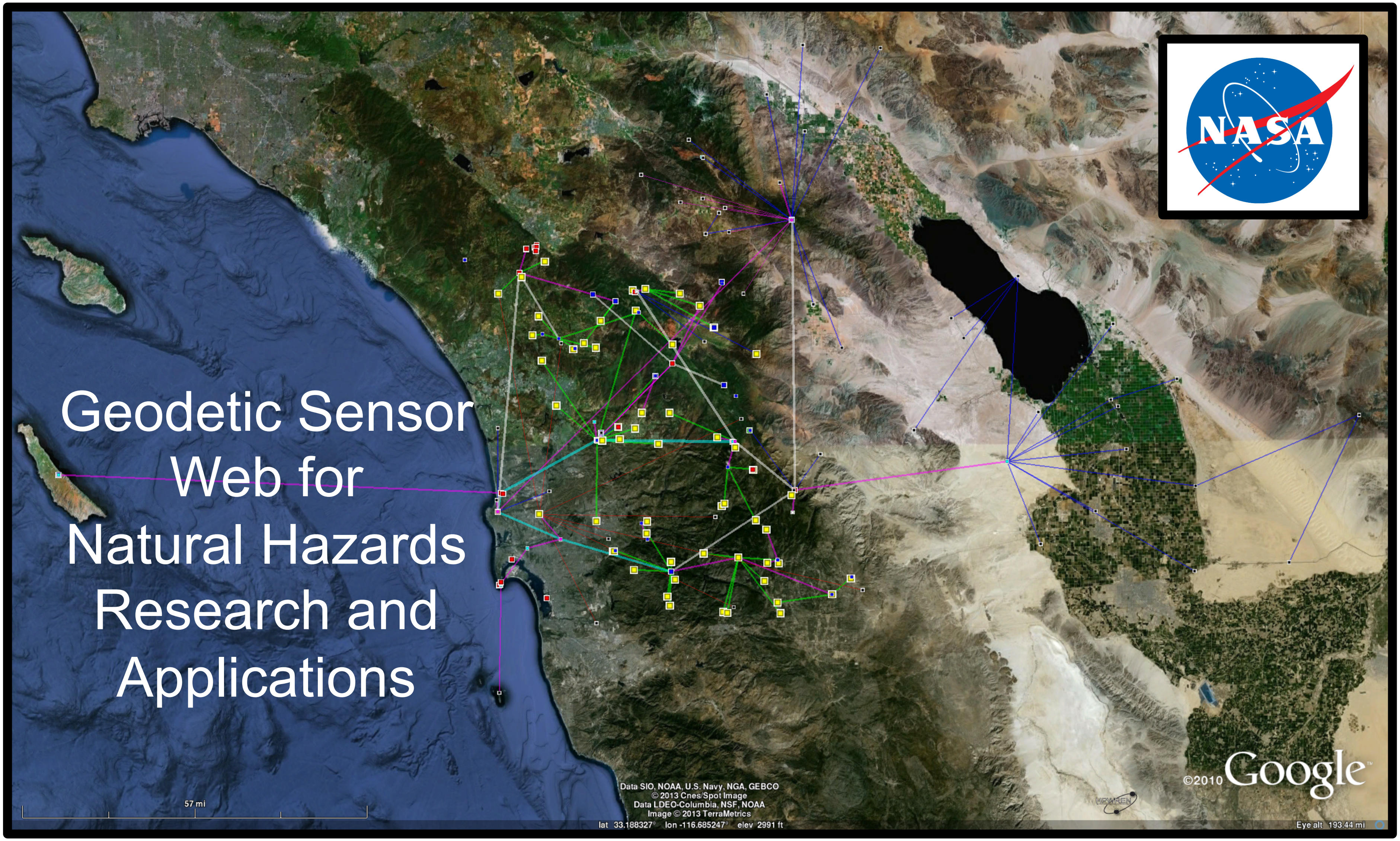
Geodetic Sensor Web for Natural Hazards Research and Applications



J.S. Haase, Y. Bock, J. Geng, A. Moore, G. Offield, M. Squibb, I. Small, S. Gutman, J. Laber, E. Yu, R. Clayton, S. Kedar

Scripps Institution of Oceanography

Jet Propulsion Laboratory, NOAA National Weather Service, Caltech

Earth Science Technology Office

AIST-11-0072

Objectives

- *Background:* Extensive existing permanent Global Positioning System (GPS) receiver sites for tectonic plate motion monitoring
- *Objective:* Enhance capabilities to transform sites into a sensor web that provides real-time information to users for rapid response to natural hazards.
- *Impact:* To better forecast, assess, and mitigate risk for natural hazards, including earthquakes, tsunamis, and extreme storms and flash flooding to save lives and reduce damage to critical infrastructure.
- *Approach*: develop and deploy SIO Geodetic Modules to network additional complementary sensors; demonstrate advanced geophysical warning products; transfer technology to partner agencies.
- *Key to success:* User driven implementation

ESTO Earth Science Technology Office

Data fusion: enhance GPS technology with low-cost sensors to mitigate risk for natural hazards

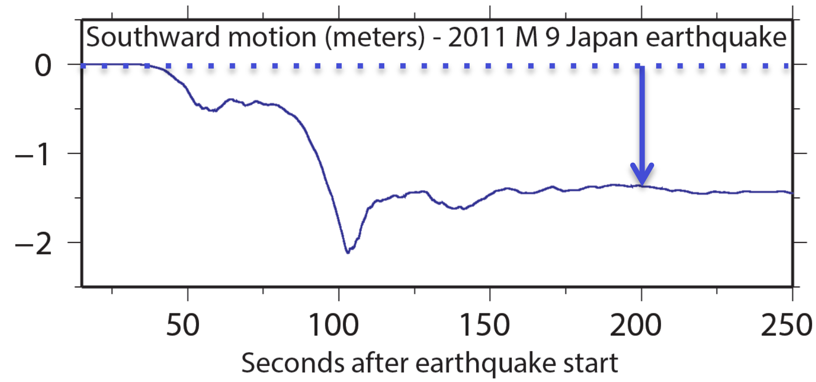
GPS
Permanent station

+

Accelerometer

=

Continuous measurements of seismic motions



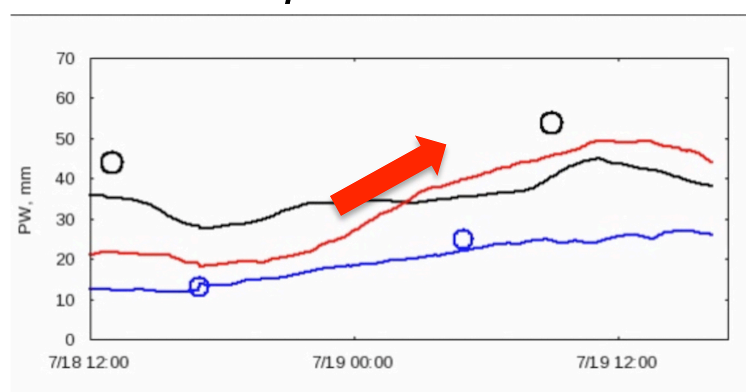
Note: GPS => GNSS

+

Meteorological Sensors (pressure, temperature)

=

Continuous monitoring of atmospheric moisture



User-driven implementation with AIST demonstration partners

Demonstration partners

\+

Accelerometer

Earthquake hazard products

CISN California Integrated Seismic Network

California's Partner to the Advanced National Seismic System ANSS

Earthquake seismology archive

GPS

\+

Meteorological Sensors (pressure, temperature)

Severe weather hazard products

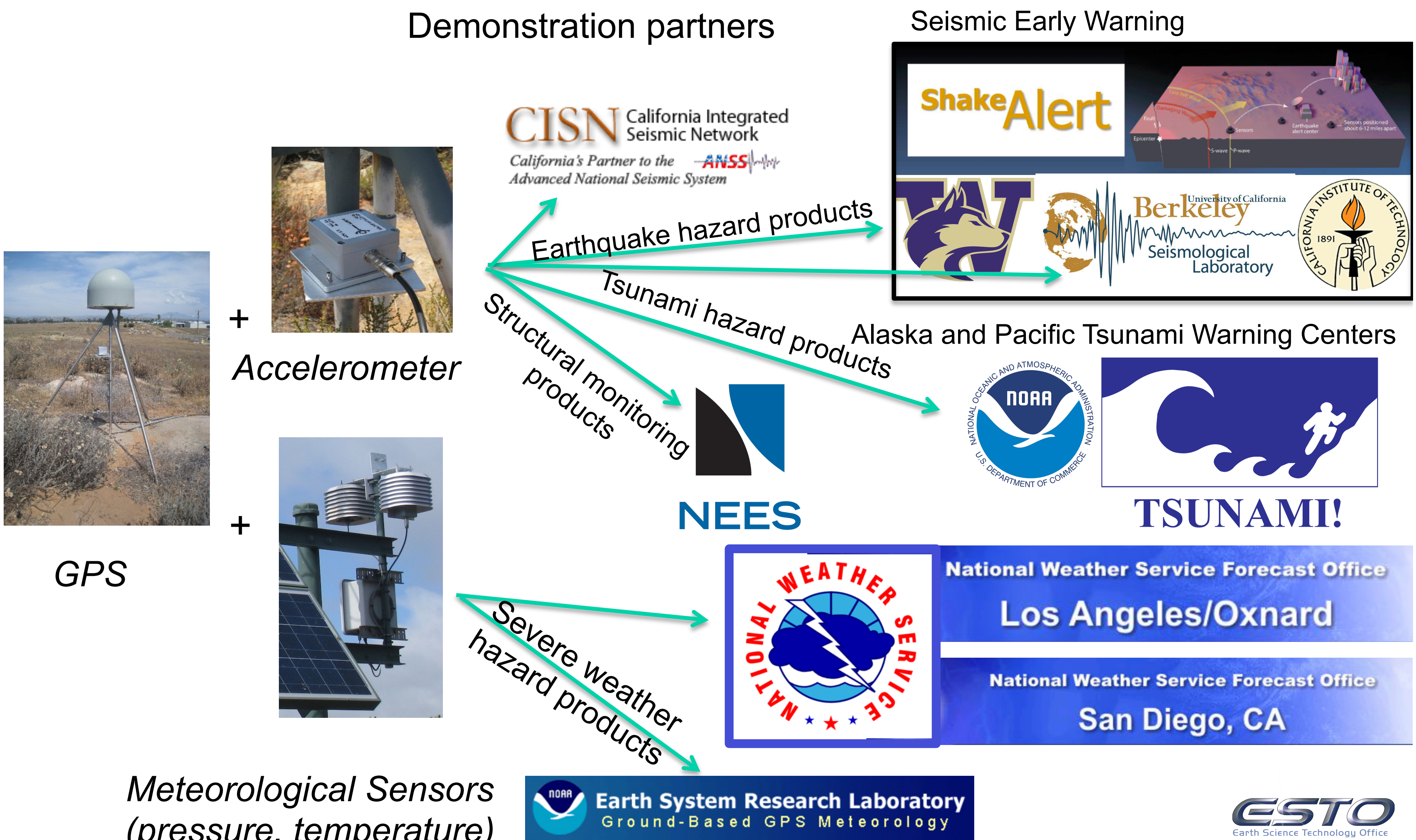
NOAA Earth System Research Laboratory
Ground-Based GPS Meteorology

National Weather Service

National Weather Service Forecast Office
Los Angeles/Oxnard

National Weather Service Forecast Office
San Diego, CA

User-driven implementation: Evolving requirements for expanded user base



ESTO Earth Science Technology Office

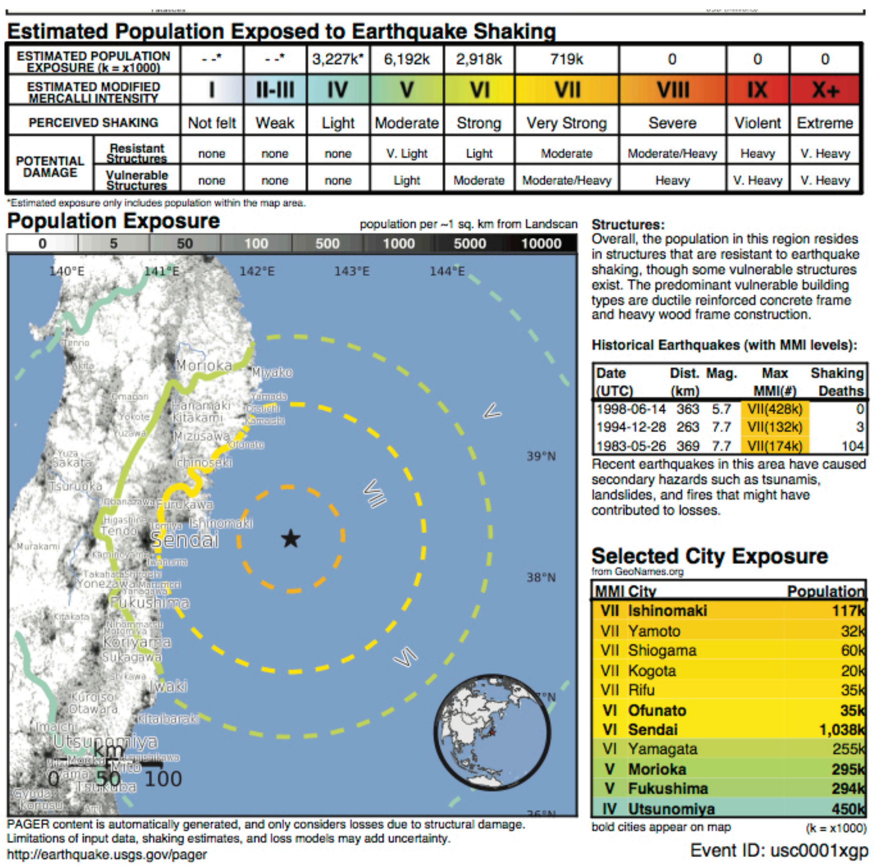
Project Phases

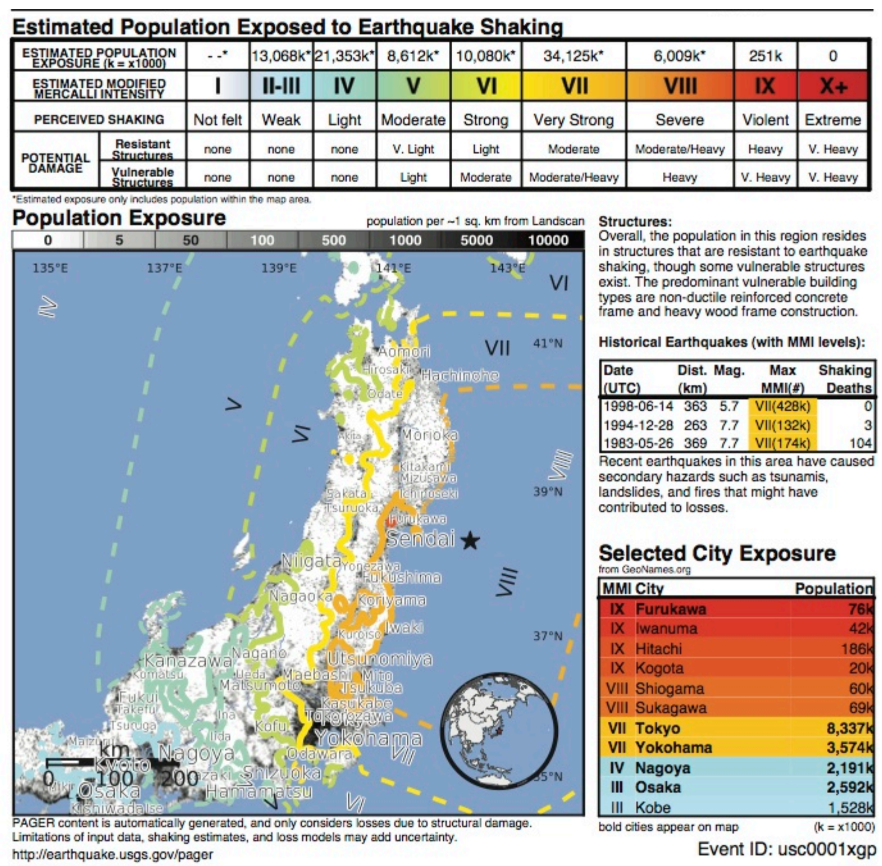
- Develop a power-efficient, low-cost, plug-in Geodetic Module to interface with MEMS accelerometer, met sensors, and other low-cost instruments (e.g. gyroscope)
- Generate on-the-fly millimeter-level ground motions and precipitable water from the geodetic module
- Develop a real-time autonomous sensor web to transmit and receive information among regional nodes, including directly to users
- Transfer capabilities to users as part of a technology infusion, for decision support and rapid response to earthquakes, tsunamis, severe storms and flash flooding

Motivation for Earthquake Hazard Technology Demonstration

M 7.9 at 9 min

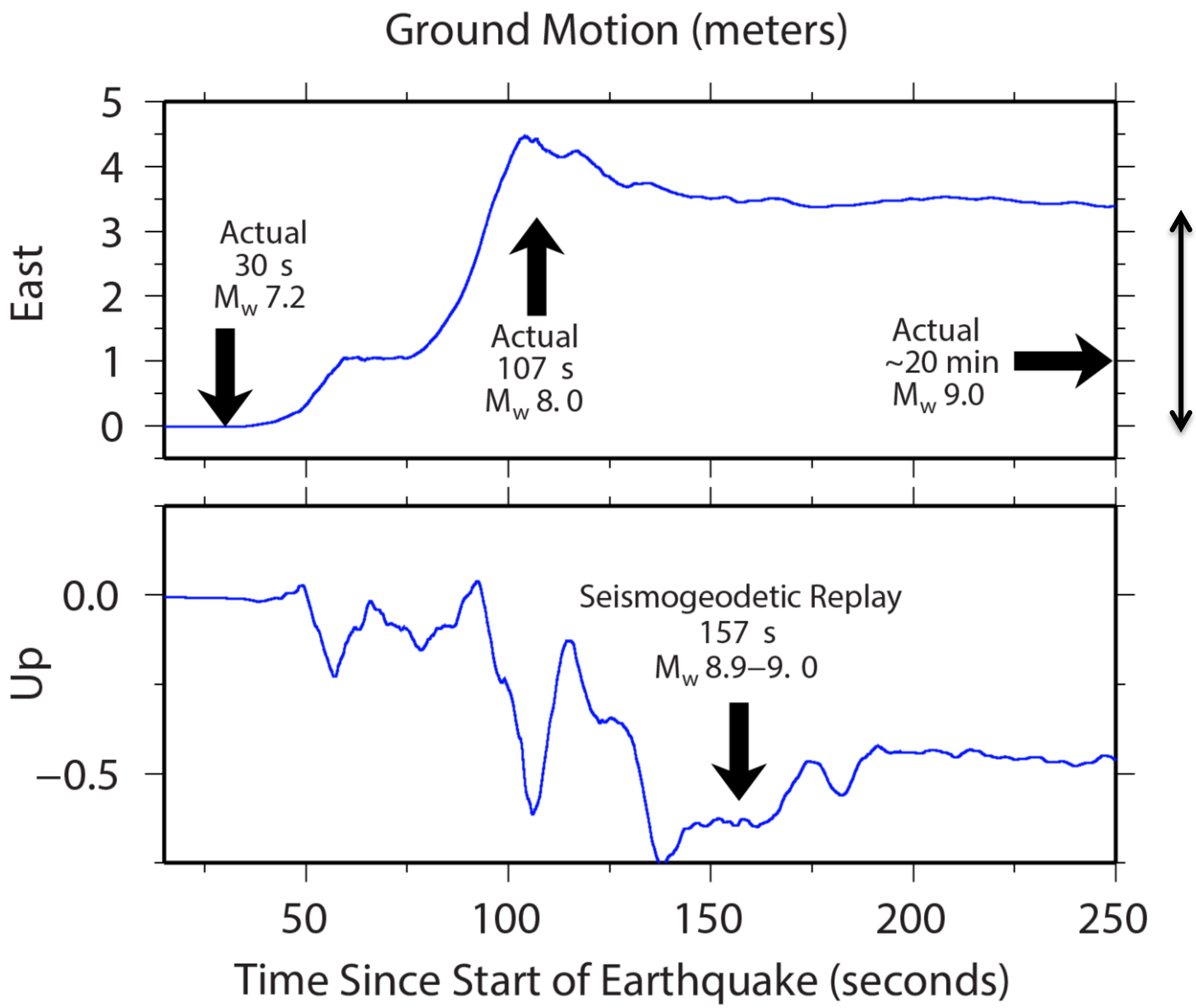
M 8.9 at 2.5 hrs





2011 Mw 9.0 Tohoku-oki earthquake was underestimated by traditional seismic methods

GPS + accelerometer sensors = seismogeodetic waveforms



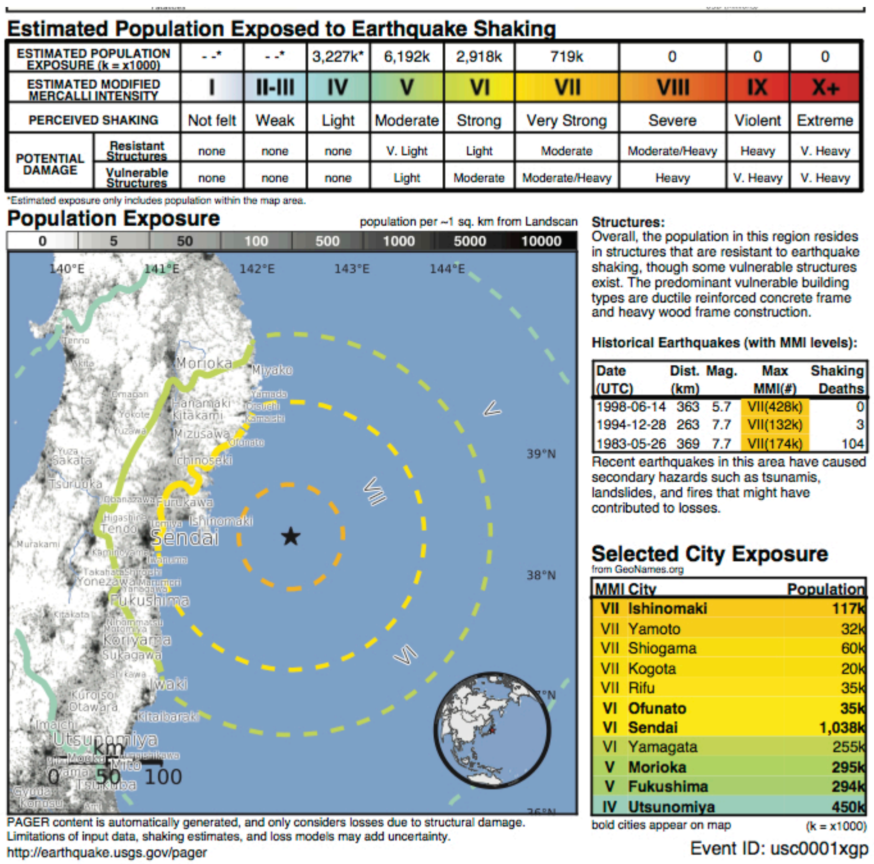
Permanent displacement is DIRECTLY related to size of rupture and slip on fault, therefore earthquake size

Our system improves on traditional seismic monitoring by estimating ground acceleration ***and permanent displacements***

Source: Melgar et al., GRL, 2013

Technology Demonstration – Earthquake and Tsunami Hazards

M 7.9 at 9 min
Traditional seismic – point source



Estimated Population Exposed to Earthquake Shaking

ESTIMATED POPULATION EXPOSURE (k = x1000)		- -*	- -*	3,227k*	6,192k	2,918k	719k	0	0	0
ESTIMATED MODIFIED MERCALLI INTENSITY		I	II-III	IV	V	VI	VII	VIII	IX	X+
PERCEIVED SHAKING		Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	Resistant Structures	none	none	none	V. Light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy
	Vulnerable Structures	none	none	none	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy	V. Heavy

*Estimated exposure only includes population within the map area.

Population Exposure

population per ~1 sq. km from Landscan

0 5 50 100 500 1000 5000 10000

Structures:
Overall, the population in this region resides in structures that are resistant to earthquake shaking, though some vulnerable structures exist. The predominant vulnerable building types are ductile reinforced concrete frame and heavy wood frame construction.

Historical Earthquakes (with MMI levels):

Date (UTC)	Dist. (km)	Mag.	Max MMI(#)	Shaking Deaths
1998-06-14	363	5.7	VII(428k)	0
1994-12-28	263	7.7	VII(132k)	3
1983-05-26	369	7.7	VII(174k)	104

Recent earthquakes in this area have caused secondary hazards such as tsunamis, landslides, and fires that might have contributed to losses.

Selected City Exposure
from GeoNames.org

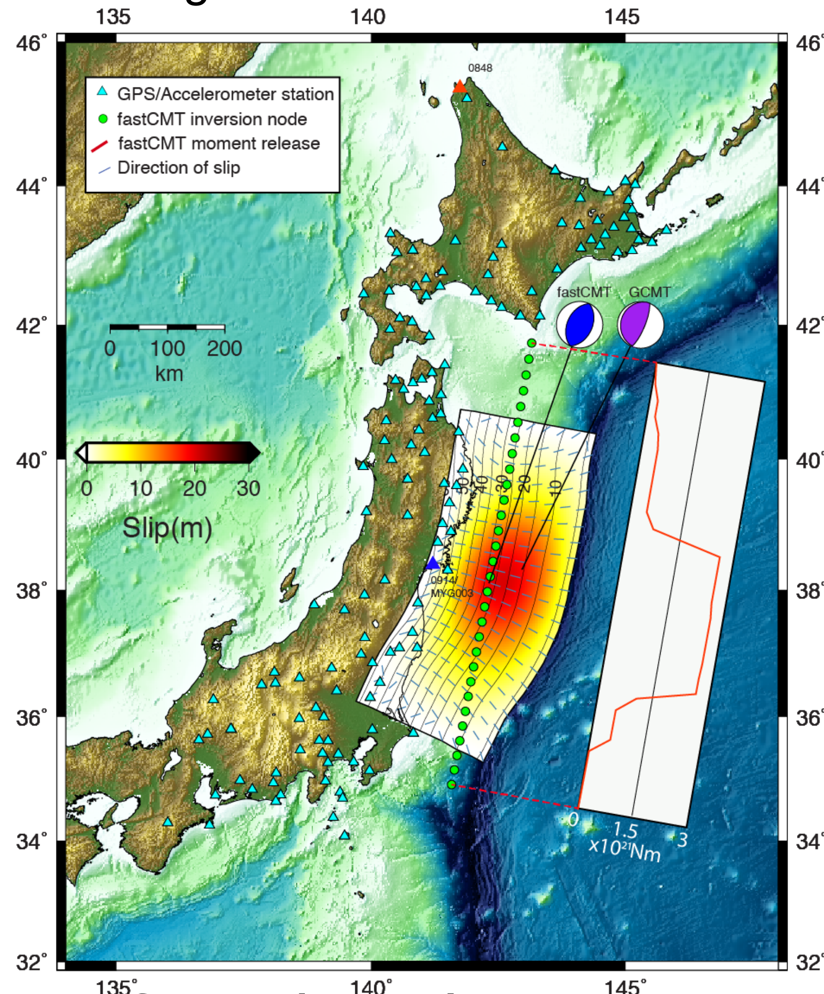
MMI	City	Population
VII	**Ishinomaki**	**117k**
VII	Yamoto	32k
VII	Shiogama	60k
VII	Kogota	20k
VII	Rifu	35k
VI	**Ofunato**	**35k**
VI	**Sendai**	**1,038k**
VI	Yamagata	255k
V	**Morioka**	**295k**
V	**Fukushima**	**294k**
IV	**Utsunomiya**	**450k**

bold cities appear on map (k = x1000)

PAGER content is automatically generated, and only considers losses due to structural damage.
Limitations of input data, shaking estimates, and loss models may add uncertainty.
http://earthquake.usgs.gov/pager

Event ID: usc0001xgp

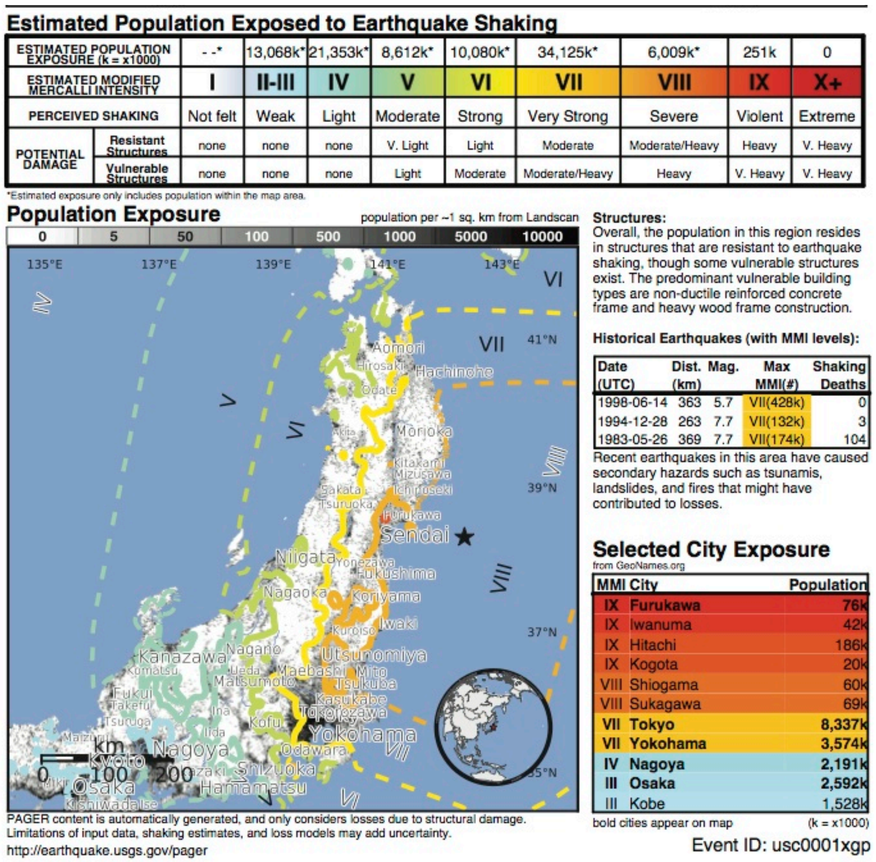
M 9 at 2.6 minutes
Seismogeodetic – extended source



Seismogeodetic data provides better estimates of finite extent of earthquake

Technology Demonstration – Earthquake and Tsunami Hazards

M 8.9 at 2.5 hours
Traditional seismic – extended source



Estimated Population Exposed to Earthquake Shaking

ESTIMATED POPULATION EXPOSURE (k = x1000)		--*	13,068k*	21,353k*	8,612k*	10,080k*	34,125k*	6,009k*	251k	0
ESTIMATED MODIFIED MERCALLI INTENSITY		I	II-III	IV	V	VI	VII	VIII	IX	X+
PERCEIVED SHAKING		Not felt	Weak	Light	Moderate	Strong	Very Strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	Resistant Structures	none	none	none	V. Light	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy
	Vulnerable Structures	none	none	none	Light	Moderate	Moderate/Heavy	Heavy	V. Heavy	V. Heavy

*Estimated exposure only includes population within the map area.

Population Exposure

population per ~1 sq. km from Landscan

0 | 5 | 50 | 100 | 500 | 1000 | 5000 | 10000

Structures:
Overall, the population in this region resides in structures that are resistant to earthquake shaking, though some vulnerable structures exist. The predominant vulnerable building types are non-ductile reinforced concrete frame and heavy wood frame construction.

Historical Earthquakes (with MMI levels):

Date (UTC)	Dist. (km)	Mag.	Max MMI(#)	Shaking Deaths
1998-06-14	363	5.7	VII(428k)	0
1994-12-28	263	7.7	VII(132k)	3
1983-05-26	369	7.7	VII(174k)	104

Recent earthquakes in this area have caused secondary hazards such as tsunamis, landslides, and fires that might have contributed to losses.

Selected City Exposure
from GeoNames.org

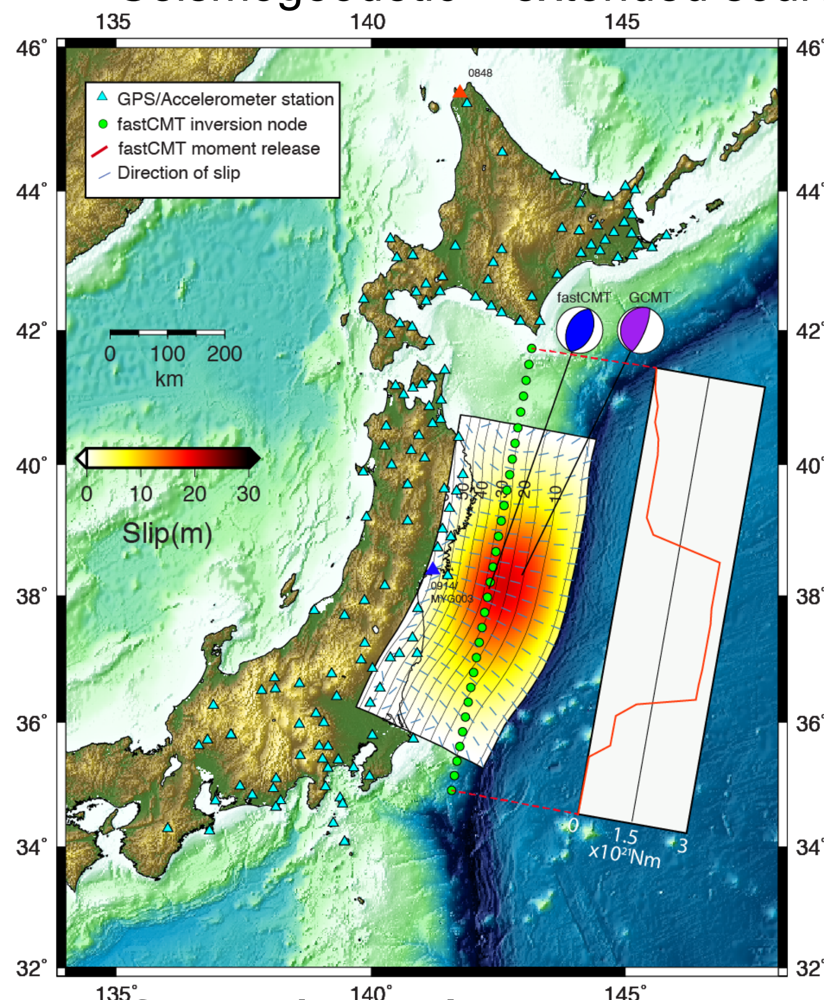
MMI	City	Population
IX	Furukawa	76k
IX	Iwanuma	42k
IX	Hitachi	186k
IX	Kogota	20k
VIII	Shiogama	60k
VIII	Sukagawa	69k
VII	**Tokyo**	8,337k
VII	**Yokohama**	3,574k
IV	**Nagoya**	2,191k
III	**Osaka**	2,592k
III	Kobe	1,528k

bold cities appear on map (k = x1000)

PAGER content is automatically generated, and only considers losses due to structural damage. Limitations of input data, shaking estimates, and loss models may add uncertainty.
http://earthquake.usgs.gov/pager

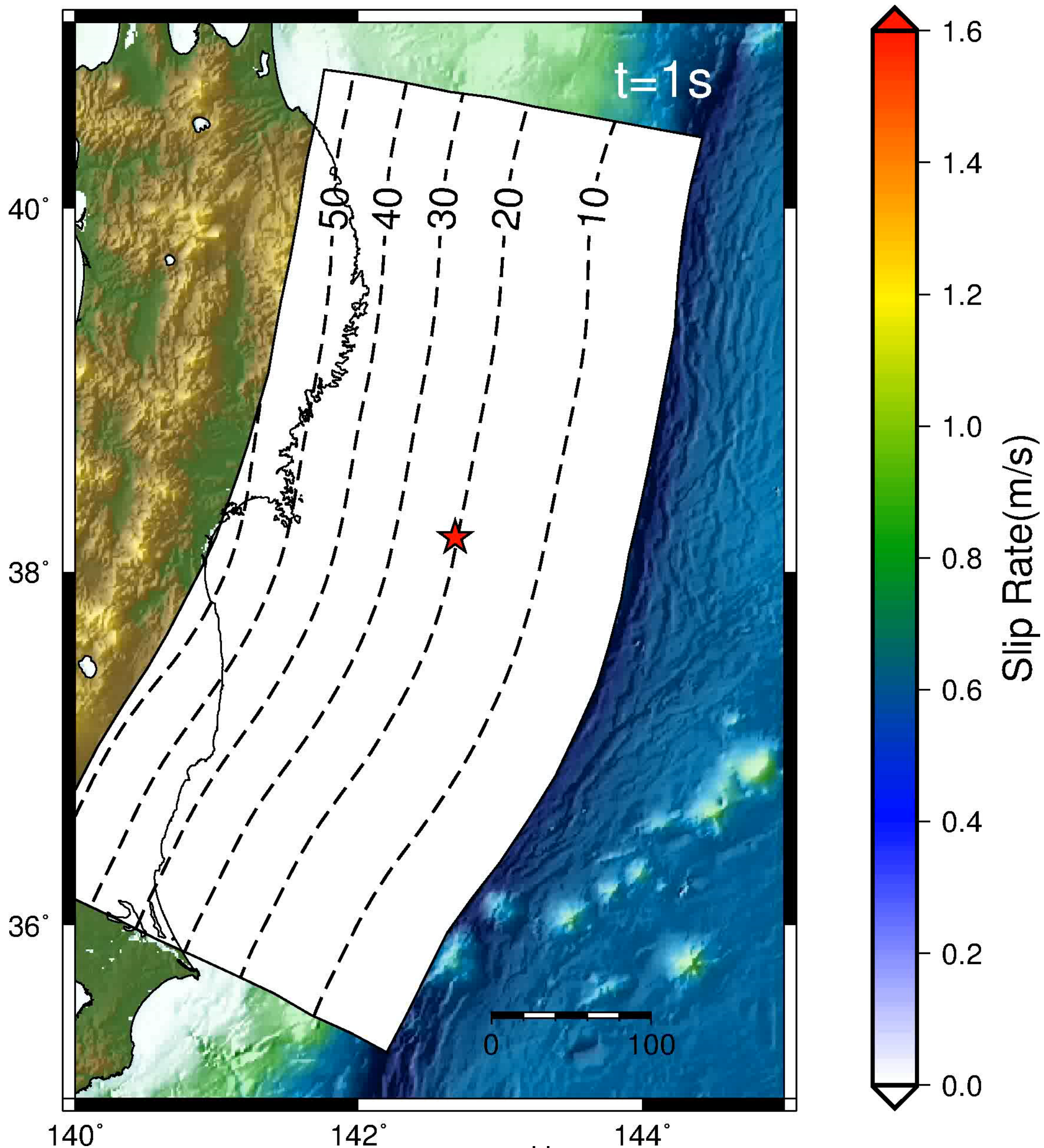
Event ID: usc0001xgp

M 9 at 2.6 minutes
Seismogeodetic – extended source

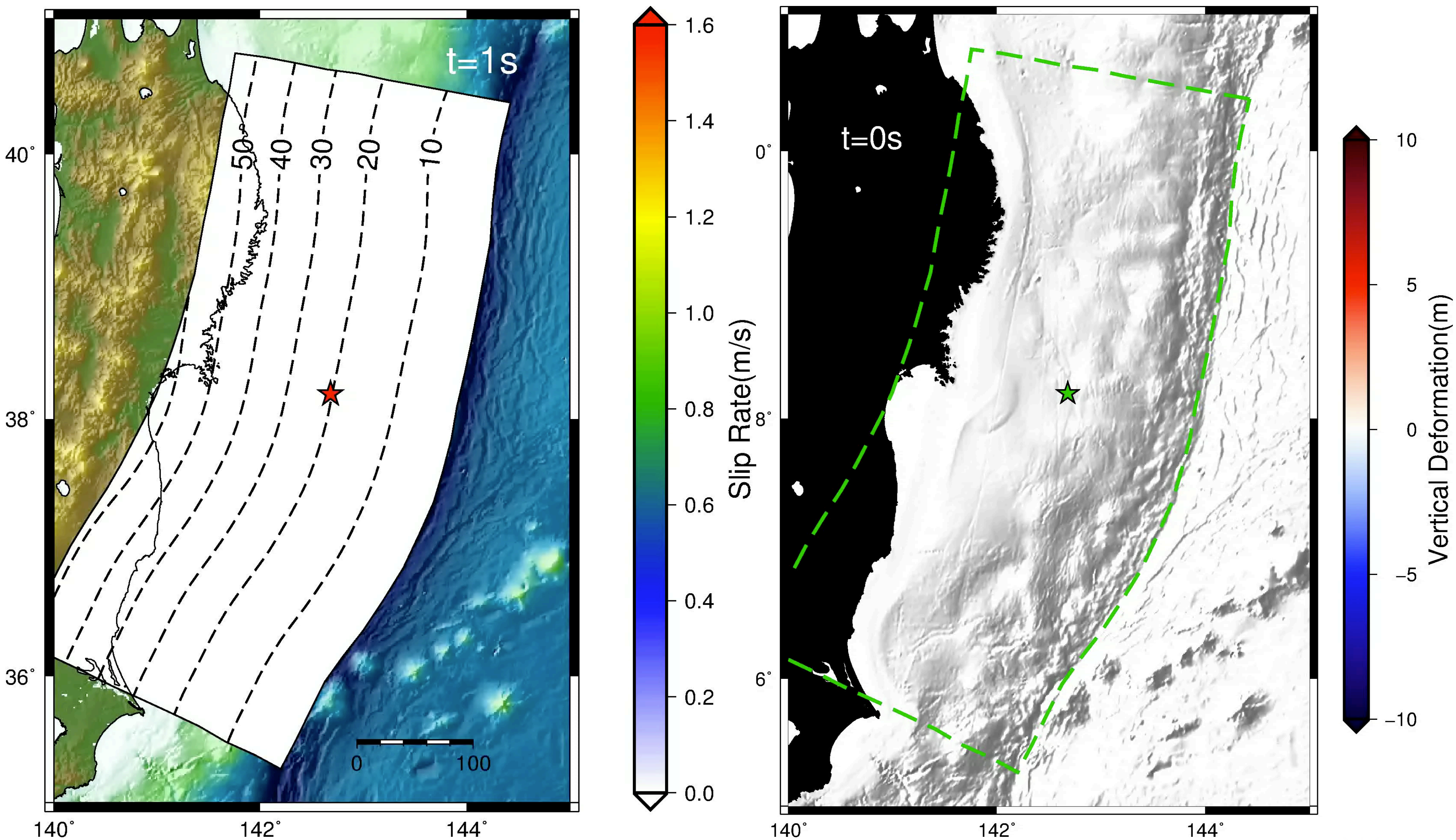


Seismogeodetic data provides better estimates of finite extent of earthquake

Technology Demonstration – Kinematic Source Inversion

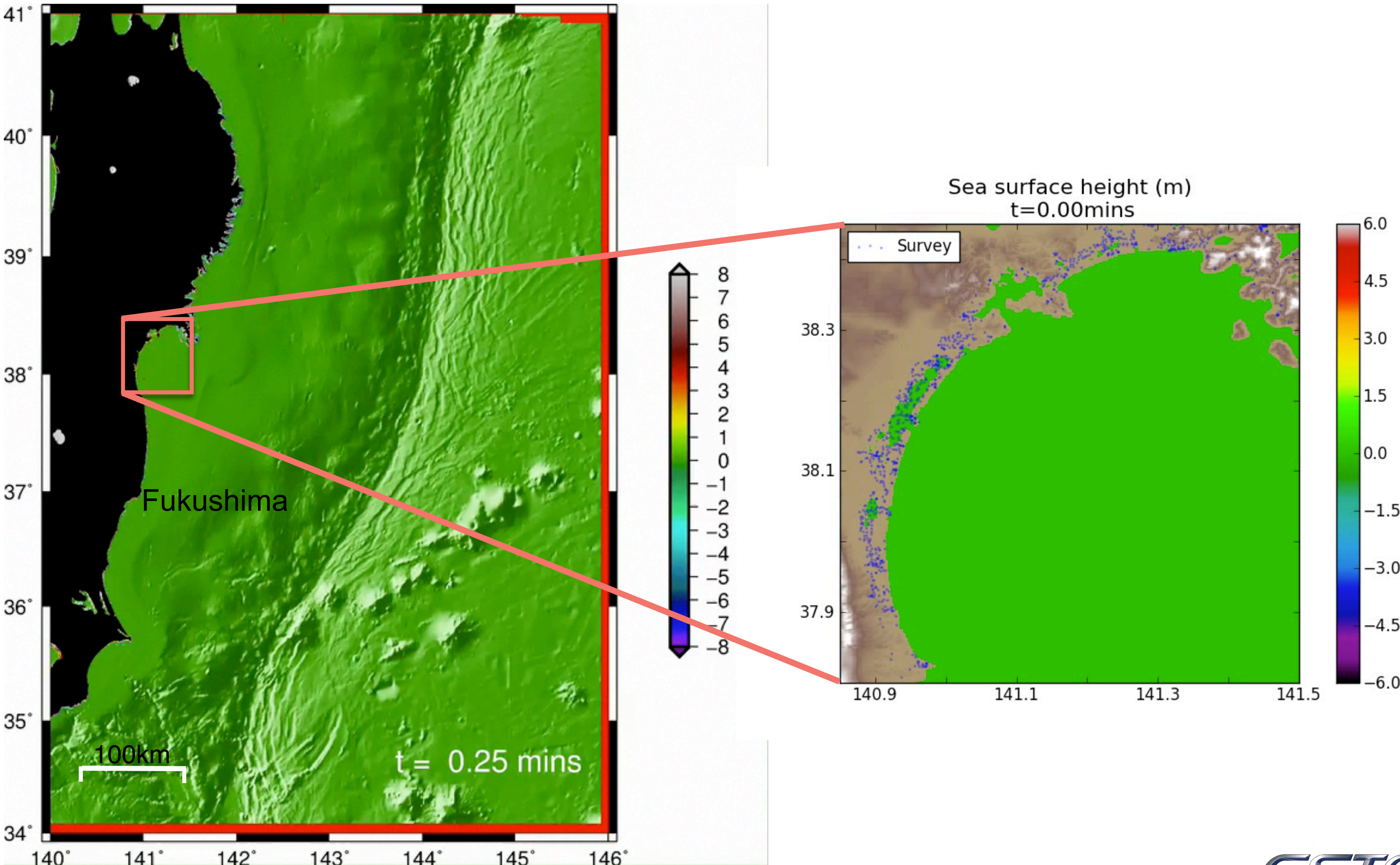


Time dependent deformation of the seafloor



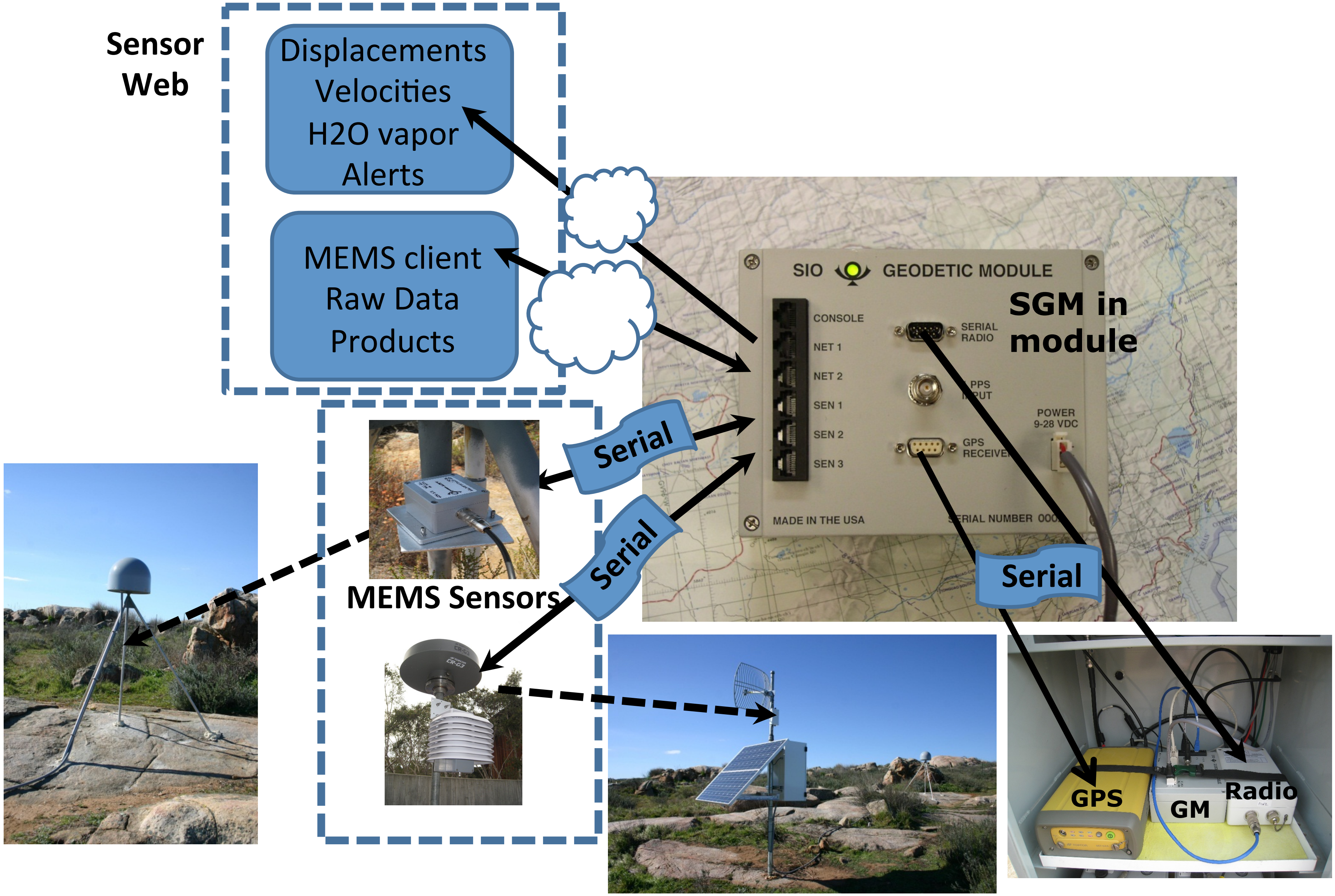
Melgar et al., in prep

Inundation prediction compared to post-event land survey



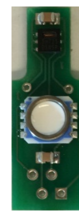
Melgar et al., in prep

Sensor technology:
Real-time autonomous sensor web



Sensor technology:
Real-time autonomous sensor web

SIO MEMS Met Package



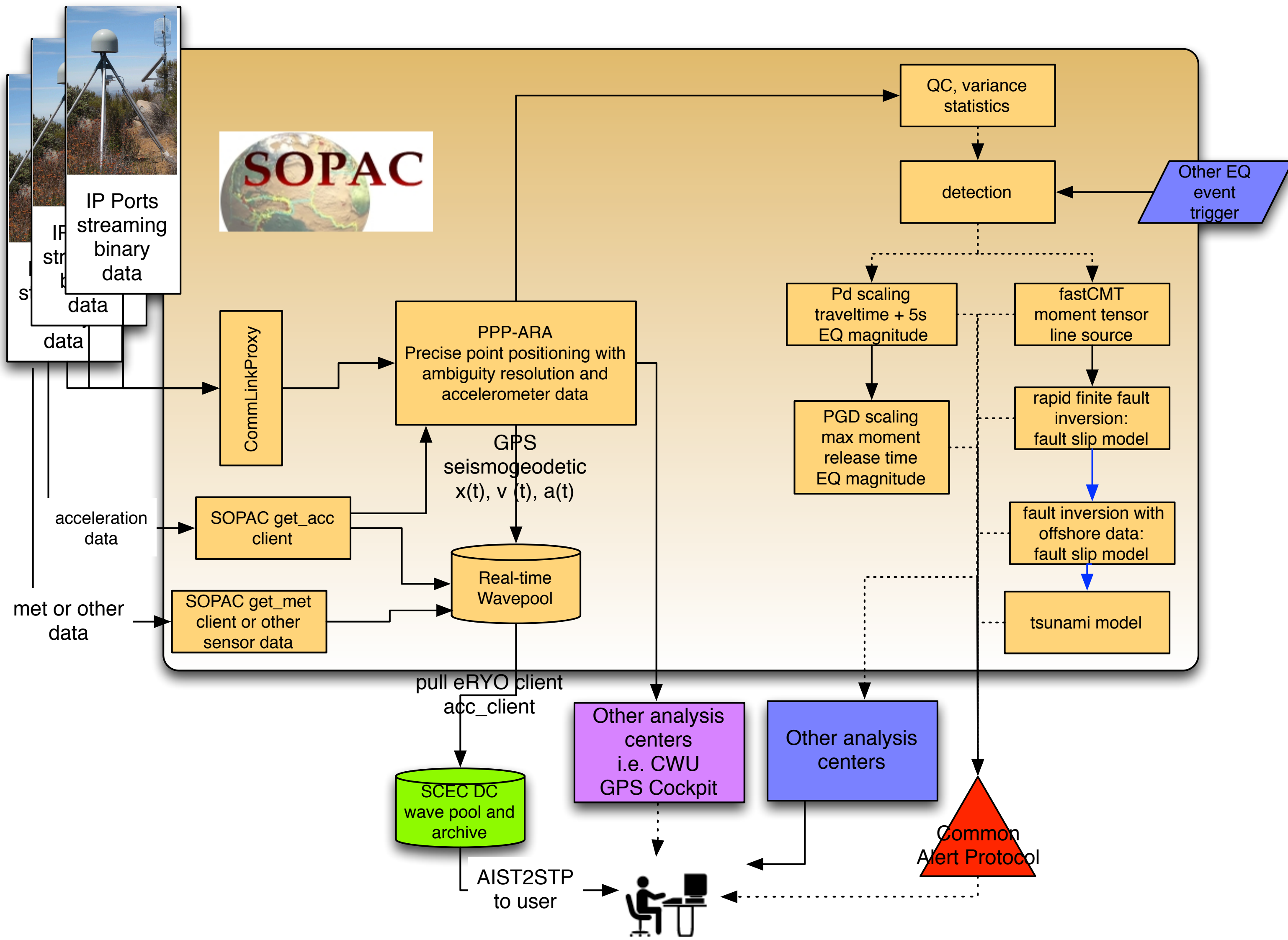
Solar Radiation Shield

Sensor Stick

RH/T
Sensirion SHT25
Barometer
Intersema MS5803-01BA

SIO Accelerometer Package 1.0 with 12-bit MEMS accelerometer. Version 2.0 will include a 16-bit MEMS accelerometer.

Information technology: Real-time analysis and exporting natural hazard products to users



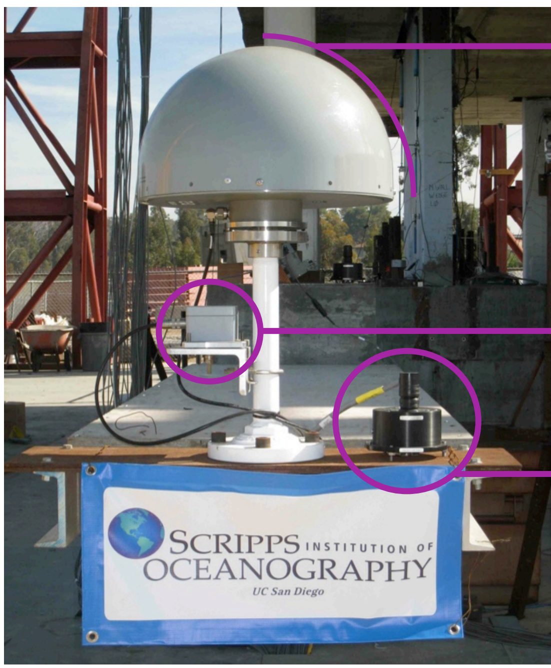
AIST demonstration

- Example 1: Building monitoring
  - technology development and testing
  - 4 story structure on NSF Network for Earthquake Engineering Simulation (NEES) shaketable
- Example 2: Earthquake hazard
  - technology implementation
  - 10 June 2016 Mw 5.2 Borrego Springs Earthquake
- Example 3: Building monitoring in the field
  - technology implementation for public/private projects
  - 3 story structure in Mexicali
- Example 4: Flash flood hazard
  - 19 July 2013 Southern California monsoon thunderstorms and flash floods

Technology development and testing

Comparison of SIO MEMS and observatory-grade accelerometers under conditions of large-amplitude shaking.

Earthquake simulations based on the
1979 M_w6.6 Imperial Valley (PGA 0.52g) &
1989 M_w6.9 Loma Prieta events (PGA 0.57g)



Collocated foundation instruments

GNSS antenna

Recorded10 Hz GPS observations.

SIO GAP containing MEMS accelerometer

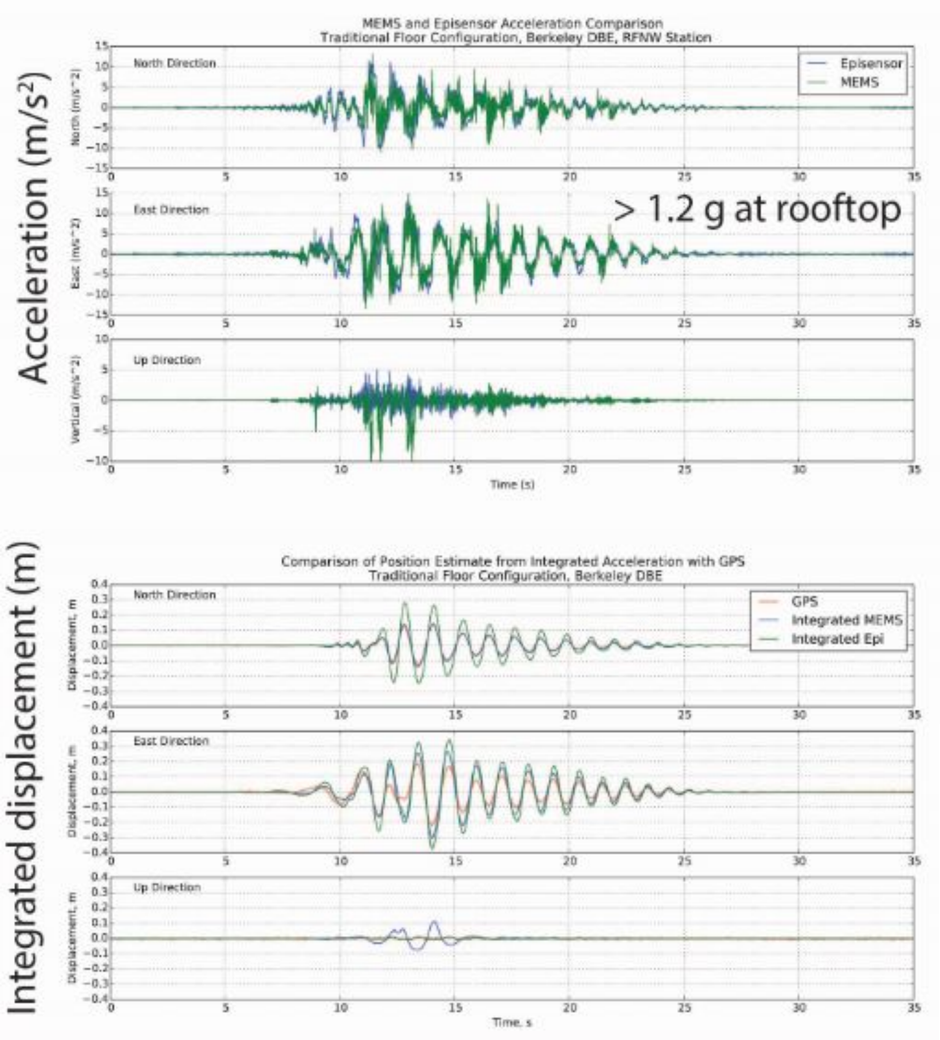
Kinemetrics EpiSensor accelerometer

Both recorded at 100 Hz.

UC San Diego Large High-Performance Outdoor Shake Table (LHPOST)

NEES

2013-14 Shake Table Tests:
Comparison of SIO MEMS and High-End Accelerometers

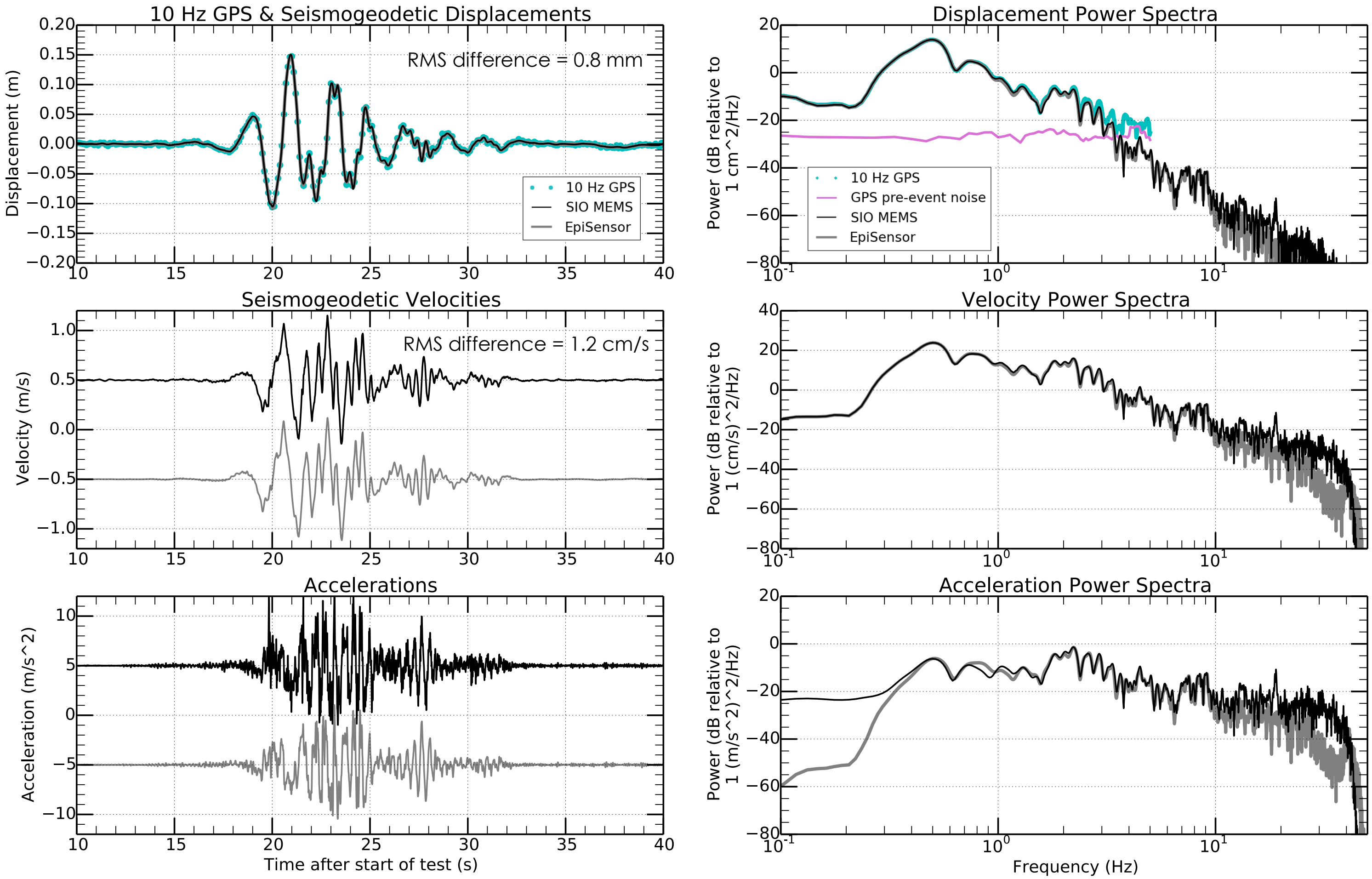


Serves the earthquake engineering and structural design community

- Enable monitoring of structures at lower cost
- Detect permanent damage
- 1.5% interstory drift defines building failure criterion
- Assesses building rotation

Technology development and testing

Demonstrate performance over BROAD frequecy range

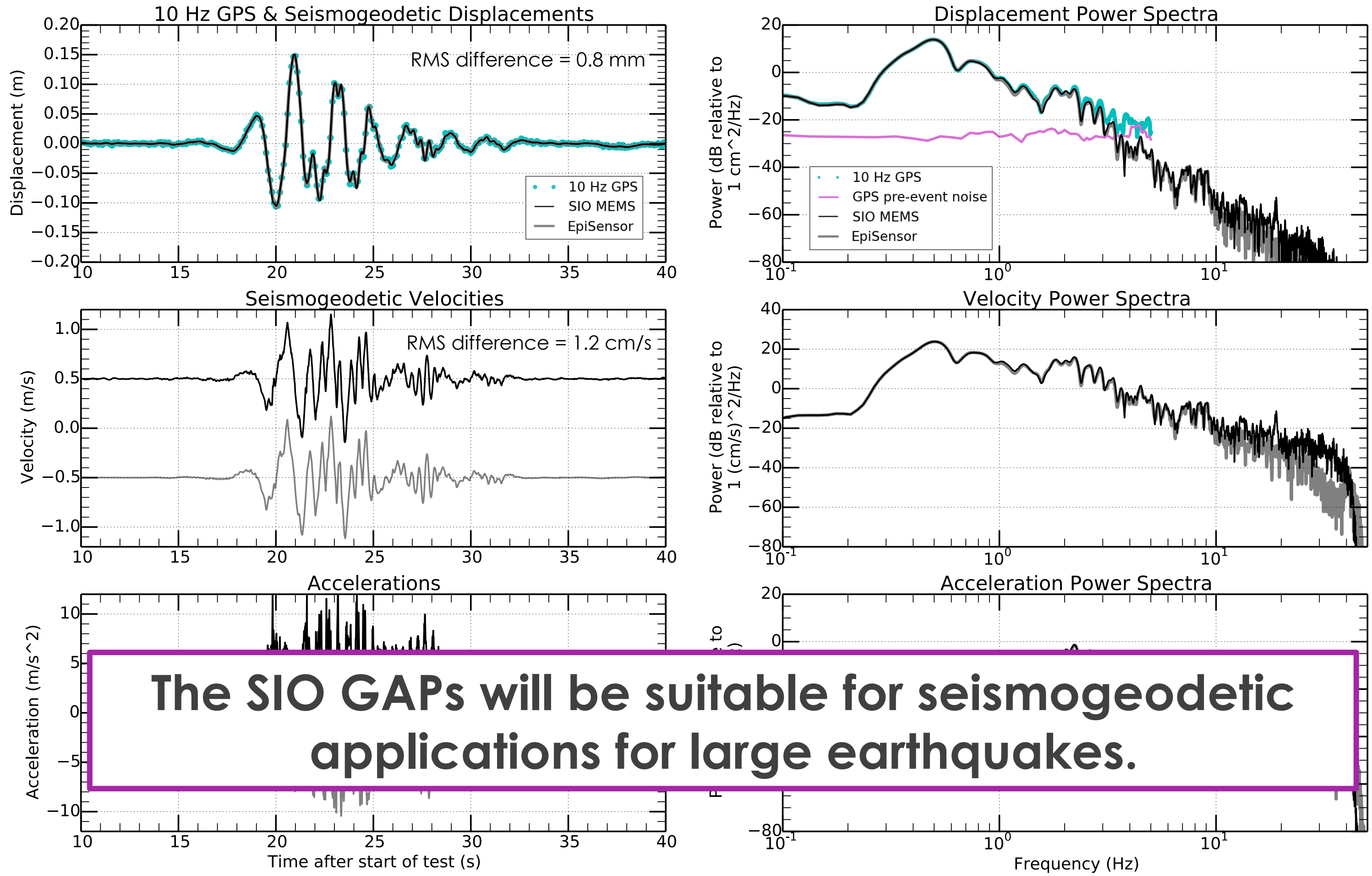


RMS differences between Foundation East component seismogeodetic solutions for all LHPOST earthquake tests:

Displacements: 1.3 ± 0.8 mm
Velocities: 1.0 ± 0.4 cm/s

Technology development and testing

Assessing the performance of the MEMS accelerometers



The SIO GAPs will be suitable for seismogeodetic applications for large earthquakes.

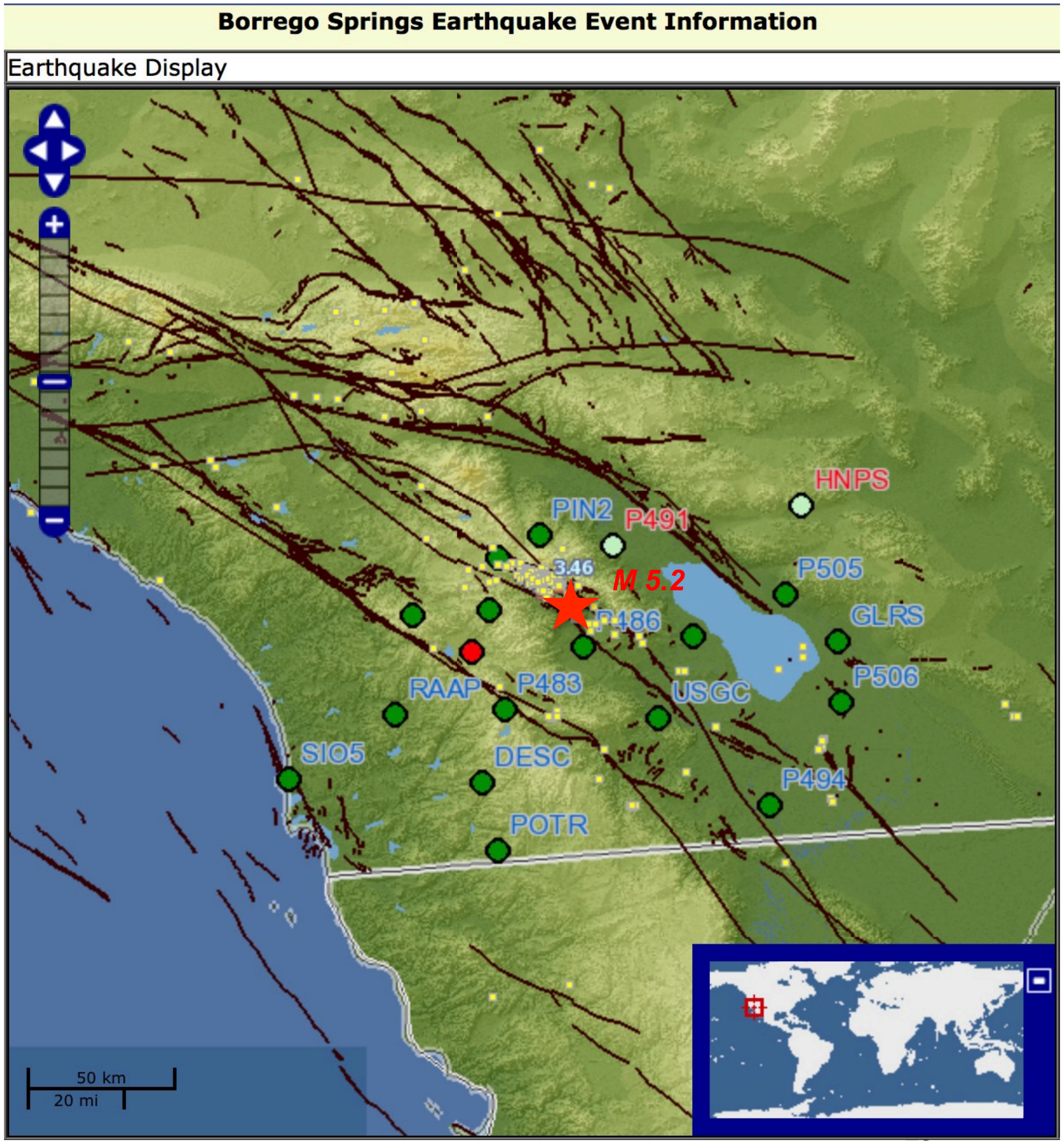
RMS differences between Foundation East component seismogeodetic solutions for all LHPOST earthquake tests:

Displacements: 1.3 ± 0.8 mm
Velocities: 1.0 ± 0.4 cm/s

AIST demonstration

- Example 1: Building monitoring
  - technology development and testing
  - 4 story structure on NSF Network for Earthquake Engineering Simulation (NEES) shaketable
- Example 2: Earthquake hazard
  - technology implementation
  - 10 June 2016 Mw 5.2 Borrego Springs Earthquake
- Example 3: Building monitoring in the field
  - technology implementation for public/private projects
  - 3 story structure in Mexicali
- Example 4: Flash flood hazard
  - 19 July 2013 Southern California monsoon thunderstorms and flash floods

Technology Implementation – San Andreas Fault



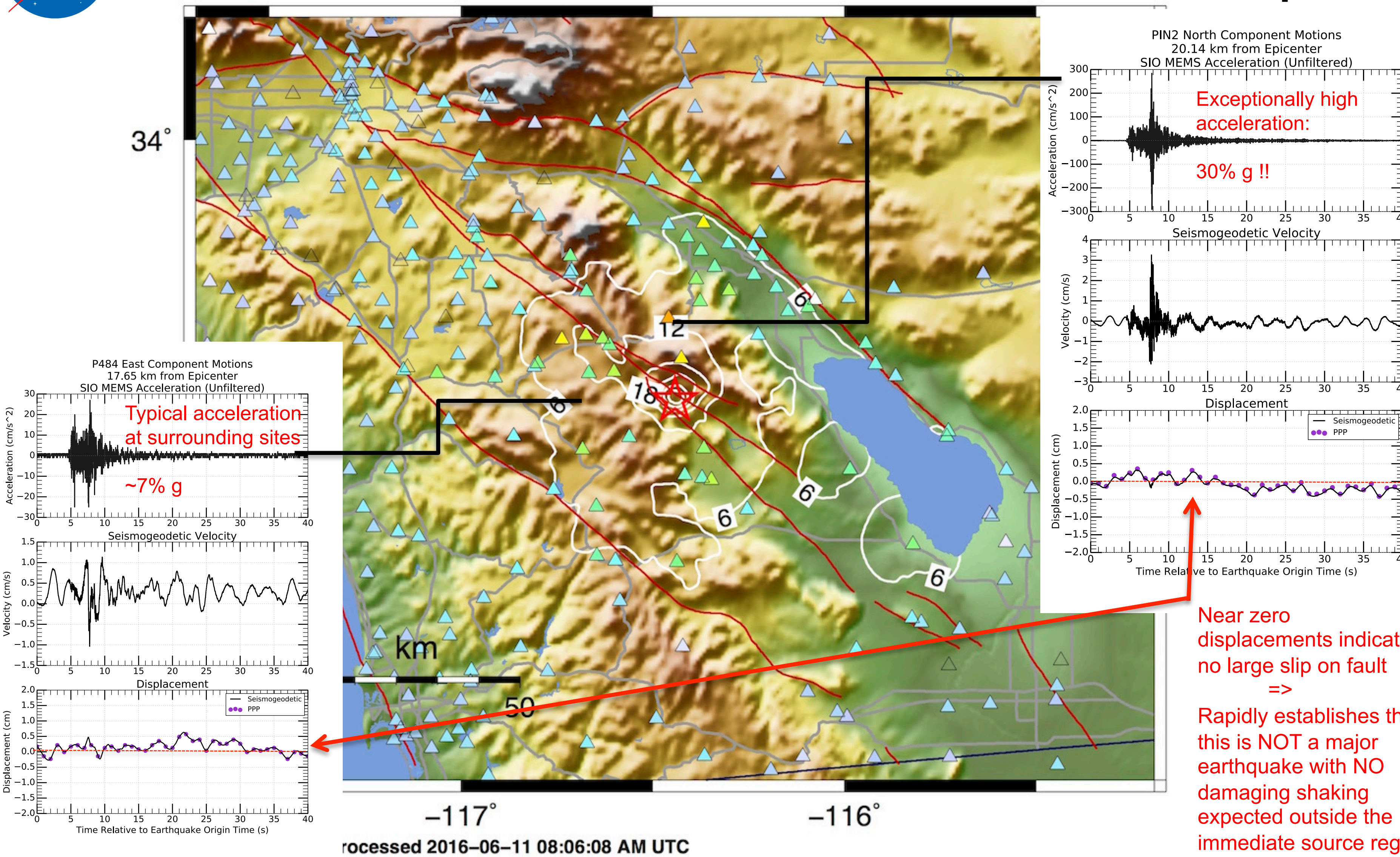
22% probability of an earthquake with M >6.5 in 30 years on the Coachella Segment of the San Andreas Fault (UCERF V3, 2014)

SIO Geodetic Modules and Accelerometer Packages have been operating at 17 stations in southern California.

Captured 10 June 2016 Mw 5.2 Borrego Springs earthquake.

ESTO Earth Science Technology Office

Real-time observations of Mw 5.2 earthquake



Near zero displacements indicate no large slip on fault

=>

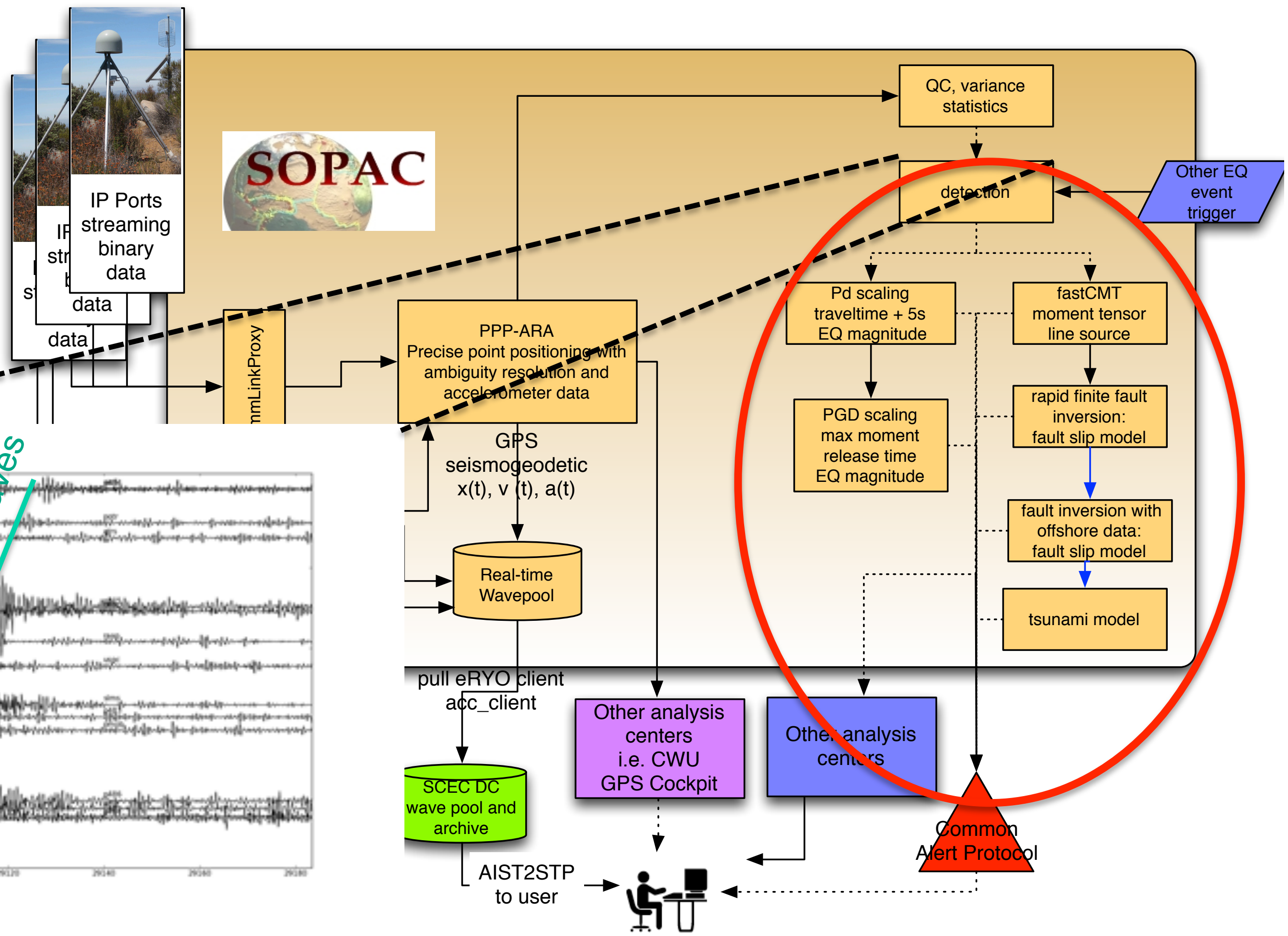
Rapidly establishes that this is NOT a major earthquake with NO damaging shaking expected outside the immediate source region

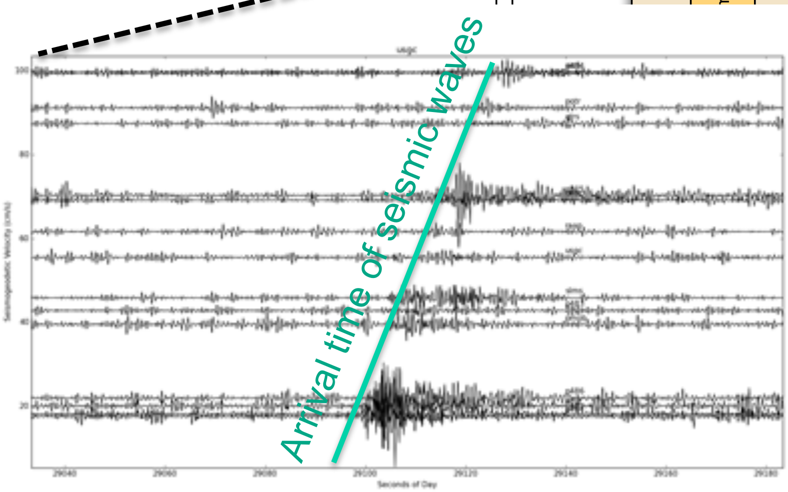
PEAK ACC.(%g)	<0.1	0.5	2.4	6.7	13	24	44	83	>156
INSTRUMENTAL INTENSITY	I	II–III	IV	V	VI	VII	VIII	IX	X+

Scale based upon Wald, et al.; 1999

Demonstrate advanced warning products: earthquake detection

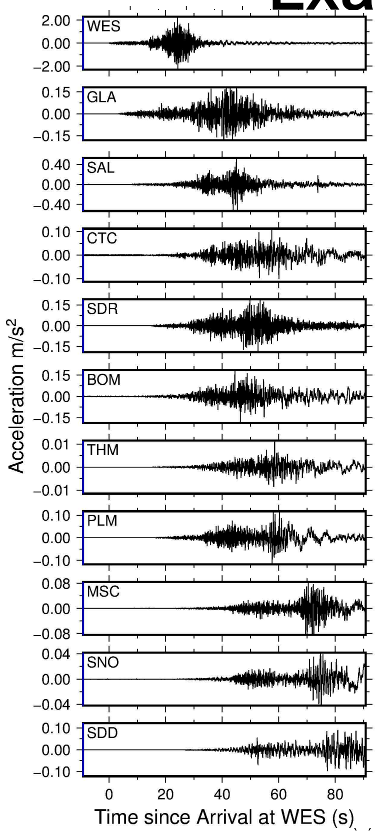
Further analysis stopped because of low amplitude arrivals in detection algorithm for M5.2 event.

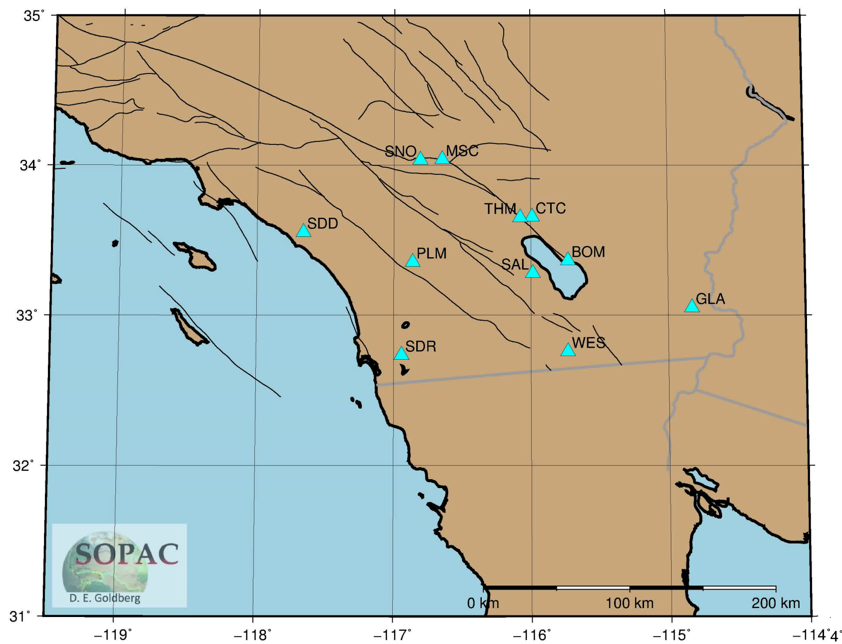




Automated real-time generation of higher level products is therefore tested with past earthquake data.

Demonstrate advanced warning products: Earthquake detection & location Example from 2010 Mw 7.2 El Mayor-Cucapah





Red circle: Propagation of *P*-wave triggering detection
Green circle: Propagation of damaging S-waves

It would take the *S* wave about 80-90 seconds after detection until it arrived in the heavily-populated regions of Riverside and Los Angeles Counties.

Magnitude estimate of Mw 7.2 is determined through peak ground displacement (PGD) magnitude scaling, updated as more information arrives.

Simulated real-time analysis for the 2010 Mw 7.2 El Mayor-Cucapah earthquake in northern Baja California, Mexico.

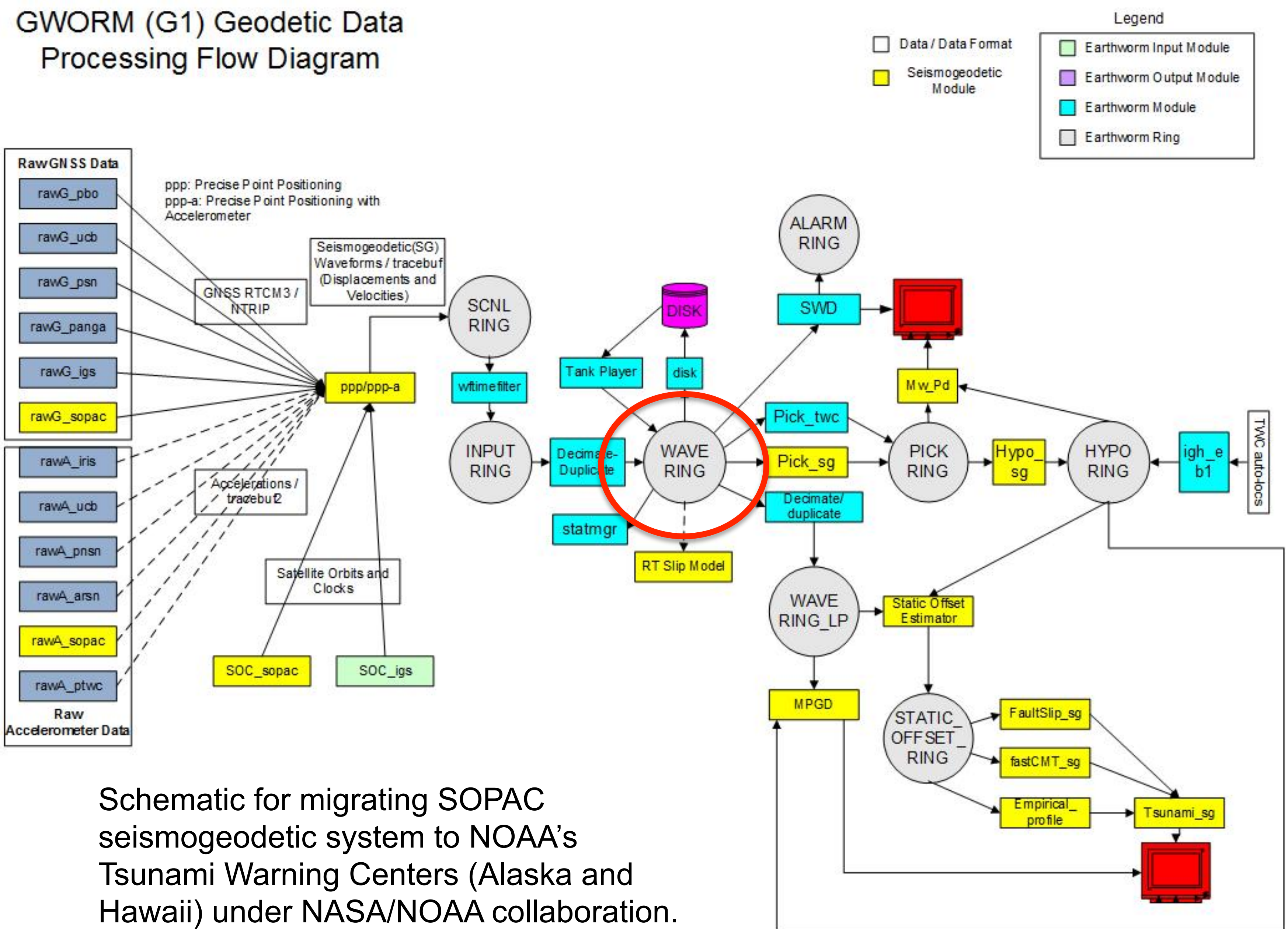
100 Hz GPS+accelerometer seismogeodetic displacement and velocity waveforms were analyzed are shown at left.

The continuous blue vertical line denotes the current epoch.

The preceding red lines indicate when the *P* wave was detected at each station.

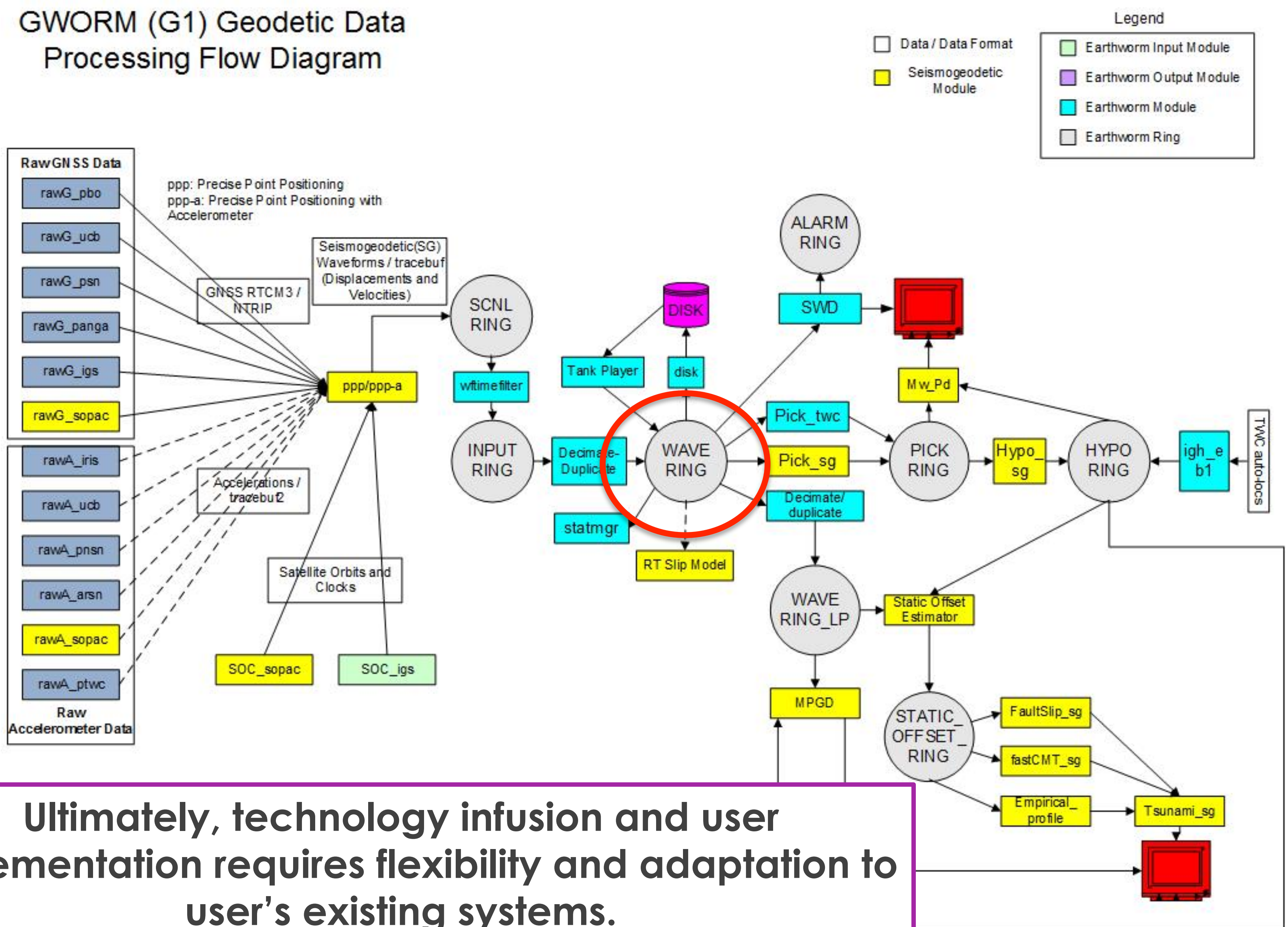
Once 4 stations have triggered, an estimate of the hypocenter can be made (yellow star).

Technology Infusion: NOAA Tsunami Early Warning System



Schematic for migrating SOPAC seismogeodetic system to NOAA's Tsunami Warning Centers (Alaska and Hawaii) under NASA/NOAA collaboration.

Technology Infusion: NOAA Tsunami Early Warning System



Ultimately, technology infusion and user implementation requires flexibility and adaptation to user's existing systems.

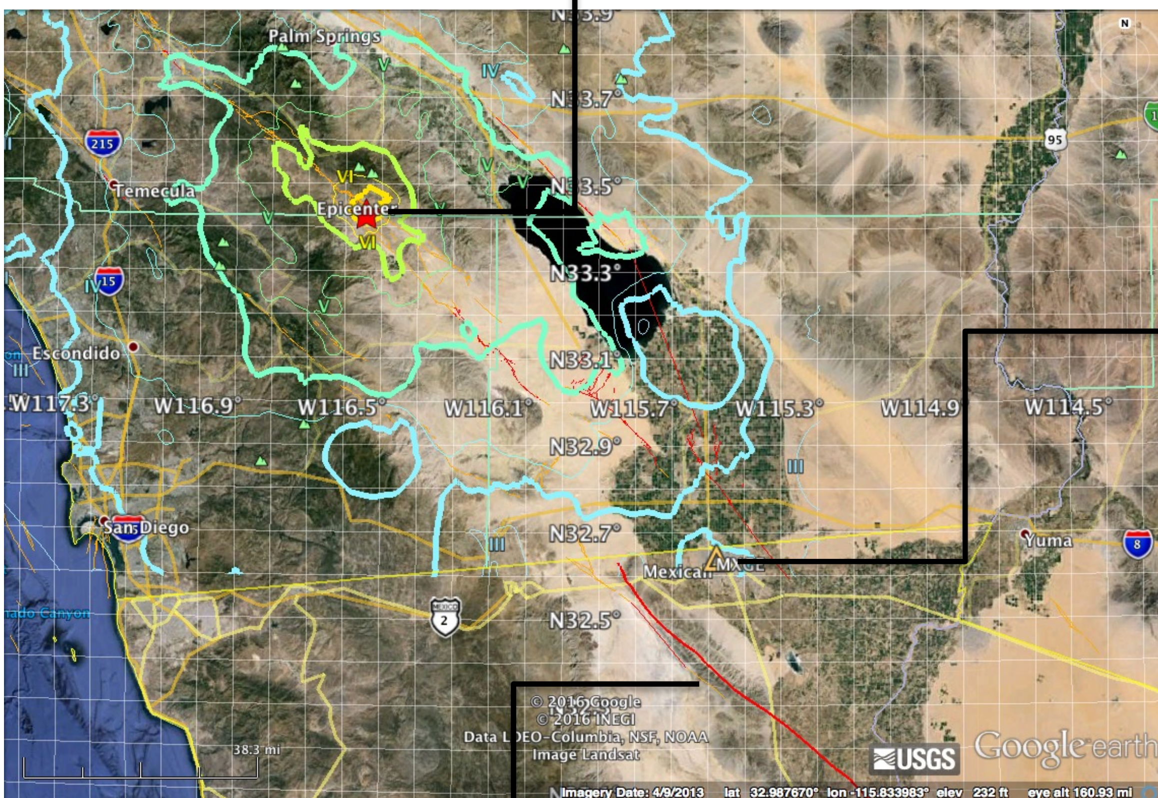
AIST demonstration

- Example 1: Building monitoring
  - technology development and testing
  - 4 story structure on NSF Network for Earthquake Engineering Simulation (NEES) shaketable
- Example 2: Earthquake hazard
  - technology implementation
  - 10 June 2016 Mw 5.2 Borrego Springs Earthquake
- Example 3: Building monitoring in the field
  - technology implementation for public/private projects
  - 3 story structure in Mexicali
- Example 4: Flash flood hazard
  - 19 July 2013 Southern California monsoon thunderstorms and flash floods

Structural Monitoring in the Field

- To demonstrate a building responds to earthquakes safely and as expected using the real-time GPS-seismic monitoring system

M 5.2 Borrego Springs Earthquake
10 June 2016



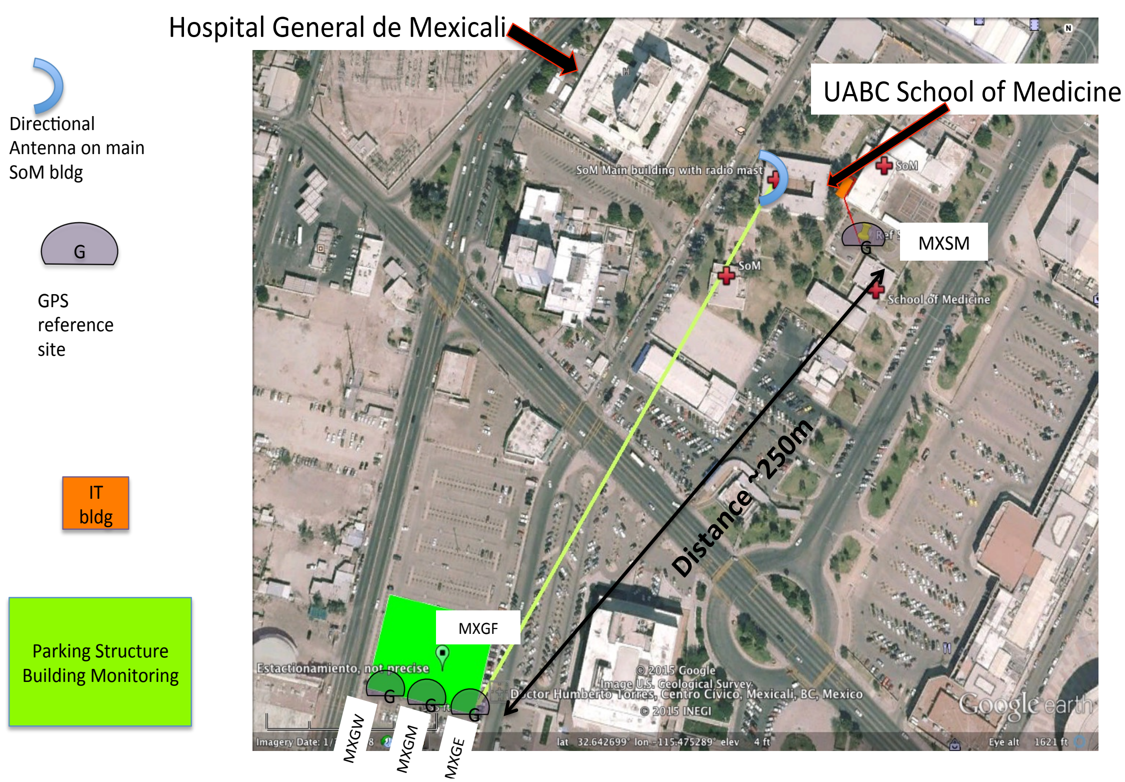
Mexicali Building Monitoring Site

M 7.2 El Mayor Cucapah Earthquake
4 April 2010

ESTO Earth Science Technology Office

Structural Monitoring in the Field

- Civic Center parking structure next door to Hospital General de Mexicali and UABC School of Medicine
- Monitored parking garage radios real-time data to UABC School of Medicine

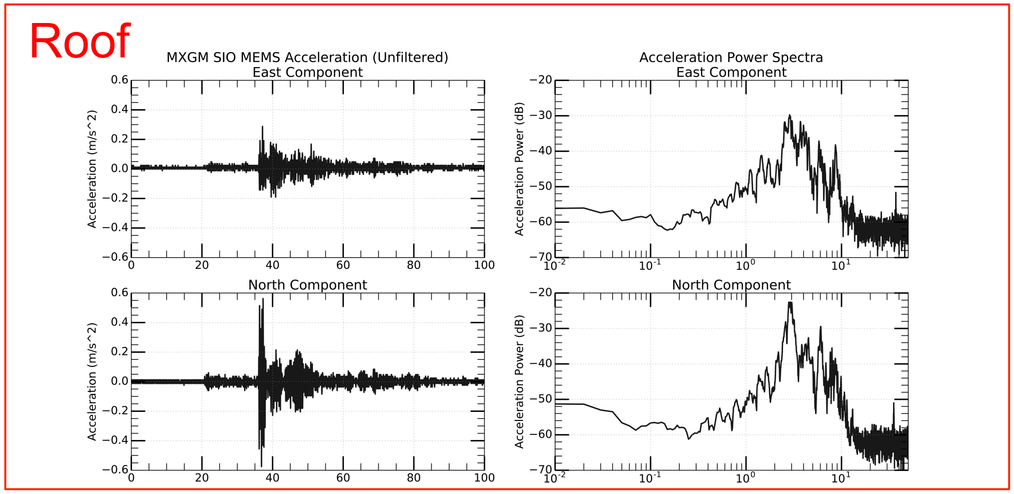


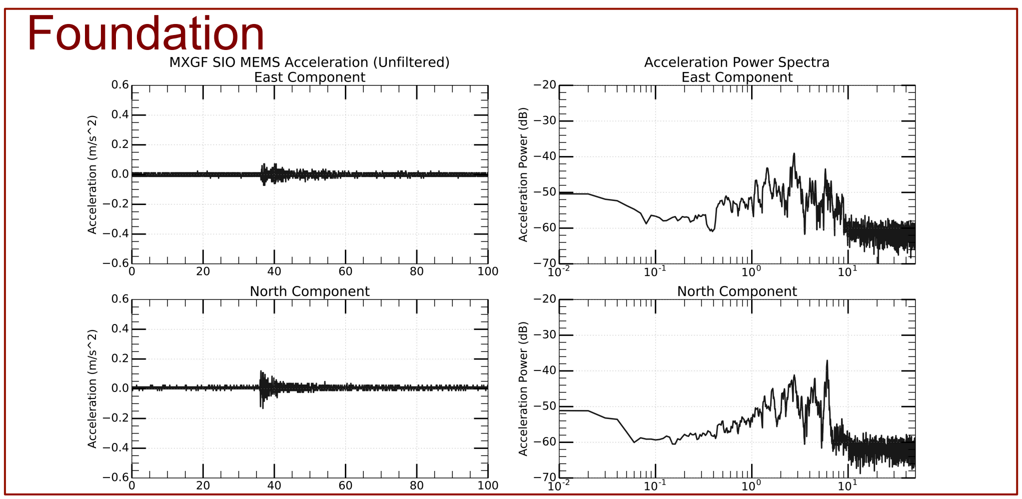
Seismogeodetic system installation

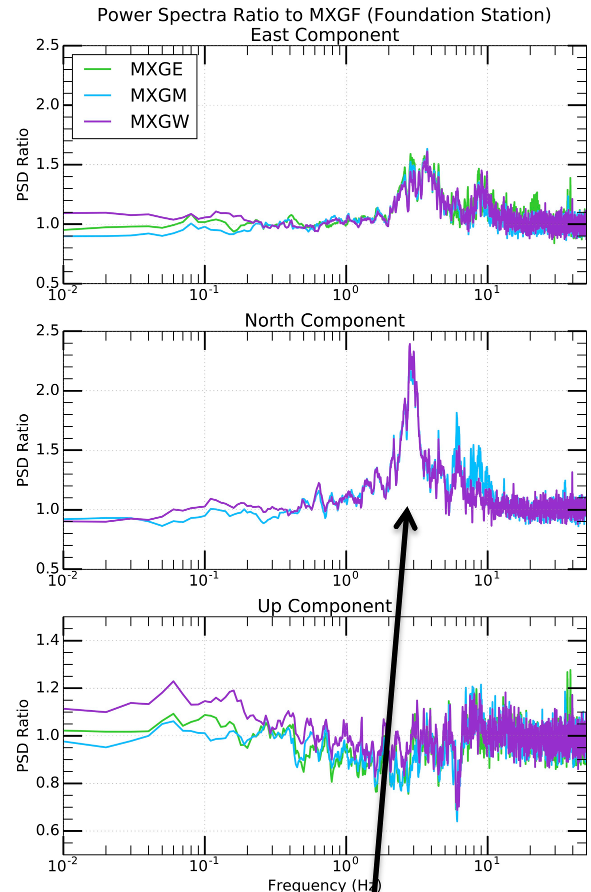
MXS1 reference site

Amplification of structure

- Access to monitoring information provides rapid assessment of building safety after M5.2 earthquake





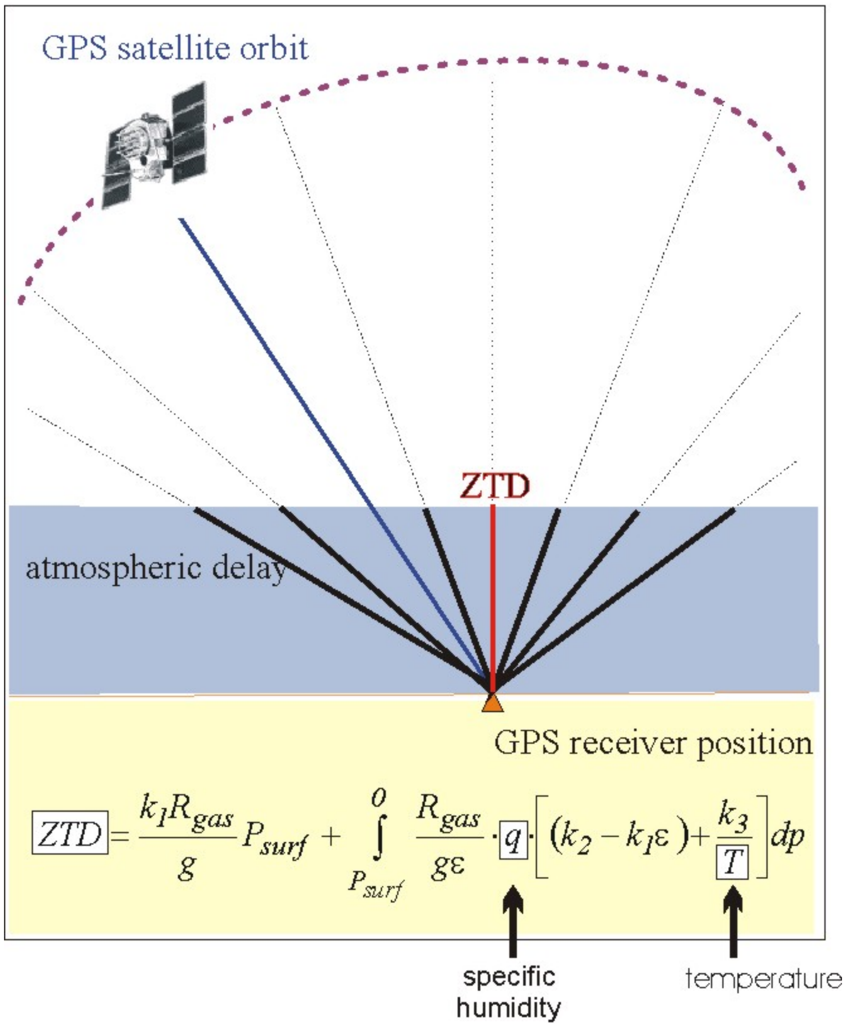


Motions amplified by ~60% in N-S component (shorter building dimension)

AIST demonstration

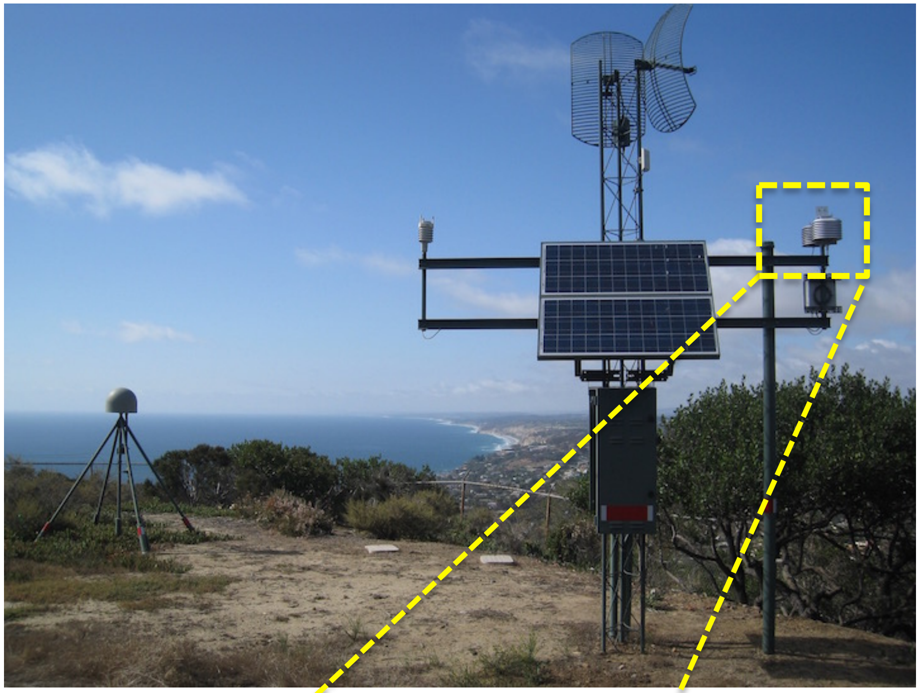
- Example 1: Building monitoring
  - technology development and testing
  - 4 story structure on NSF Network for Earthquake Engineering Simulation (NEES) shaketable
- Example 2: Earthquake hazard
  - technology implementation
  - 10 June 2016 Mw 5.2 Borrego Springs Earthquake
- Example 3: Building monitoring in the field
  - technology implementation for public/private projects
  - 3 story structure in Mexicali
- Example 4: Flash flood hazard
  - 19 July 2013 Southern California monsoon thunderstorms and flash floods

Technology Demonstration – Extreme Weather Hazards



- Signals from the GPS satellites are affected by moist air
- Position measurement requires estimating delay through atmosphere
- Automatically generate derived atmospheric water vapor above site.
- Disseminate this to NWS partners.

Technology Demonstration – Extreme Weather Hazards



Station SIO5 in La Jolla upgraded with SIO GAM

- Geodetic Module
- MEMS Accelerometer Package
- MEMS Meteorological Package

A high-end Vaisala WXT-510 Multi-Weather Sensor has been deployed for comparison with the less expensive SIO met package.

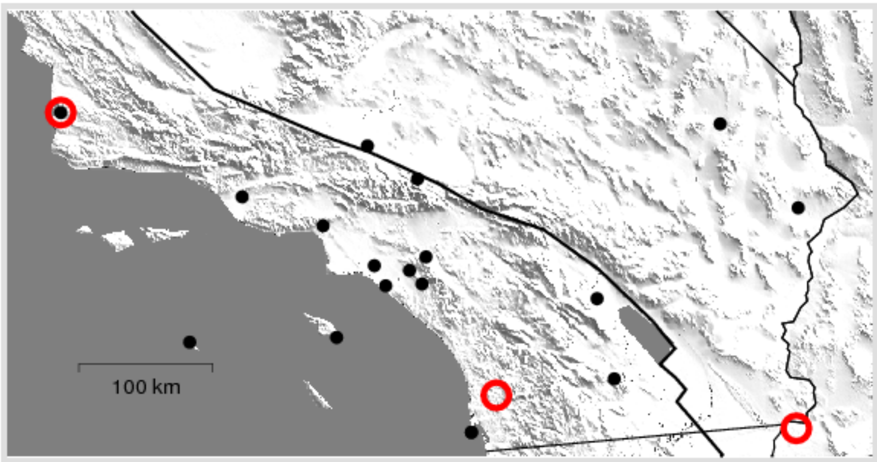
Continuously streamed to SIO

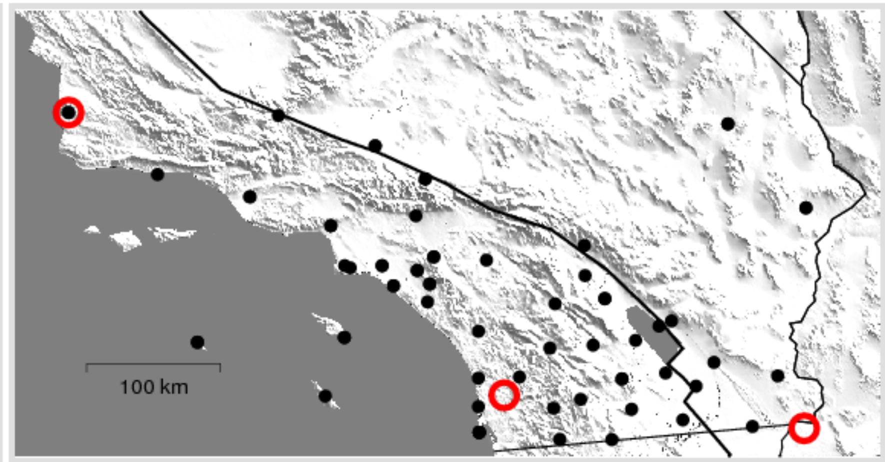
- 1 Hz GPS
- 100 Hz accelerometer data
- 10 s pressure, temperature and relative humidity data are being

The GPS and met data provide estimates of precipitable water above that location.

ESTO
Earth Science Technology Office

Technology Implementation – Augmentation of NOAA monitoring sites

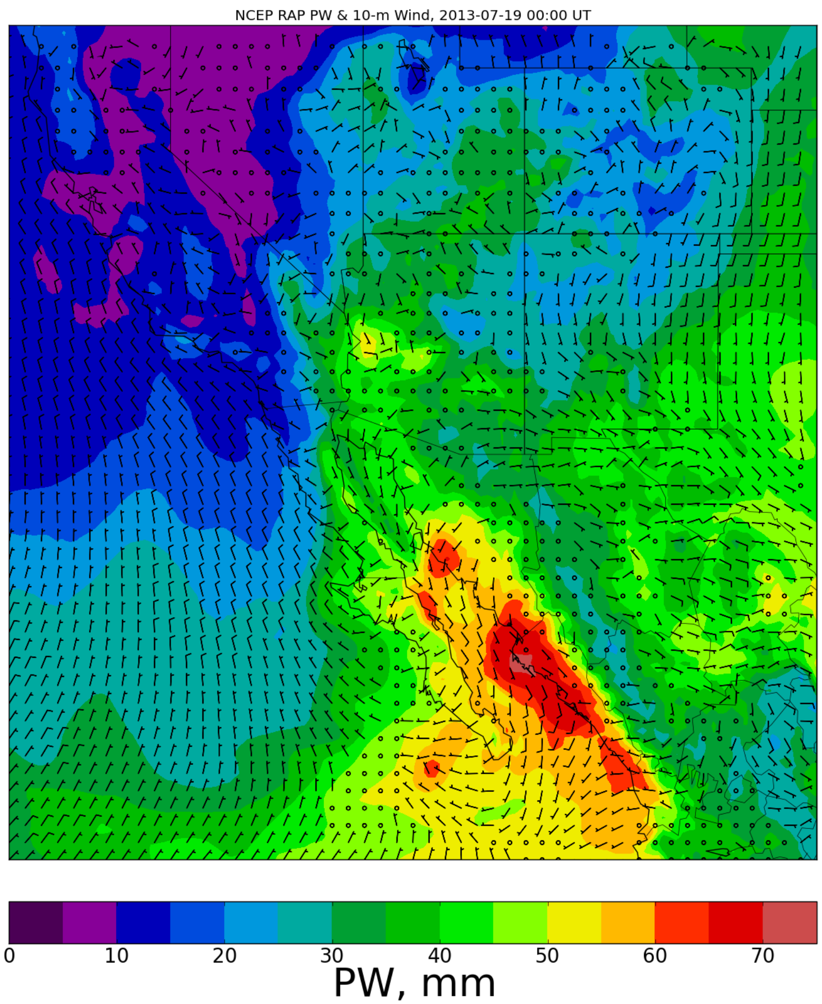




- Southern California stations analyzed by the NOAA GPS-Met project prior to the start of this AIST project.

- The station set including 37 additional stations following the implementation of AIST. Red circles indicate radiosonde sites

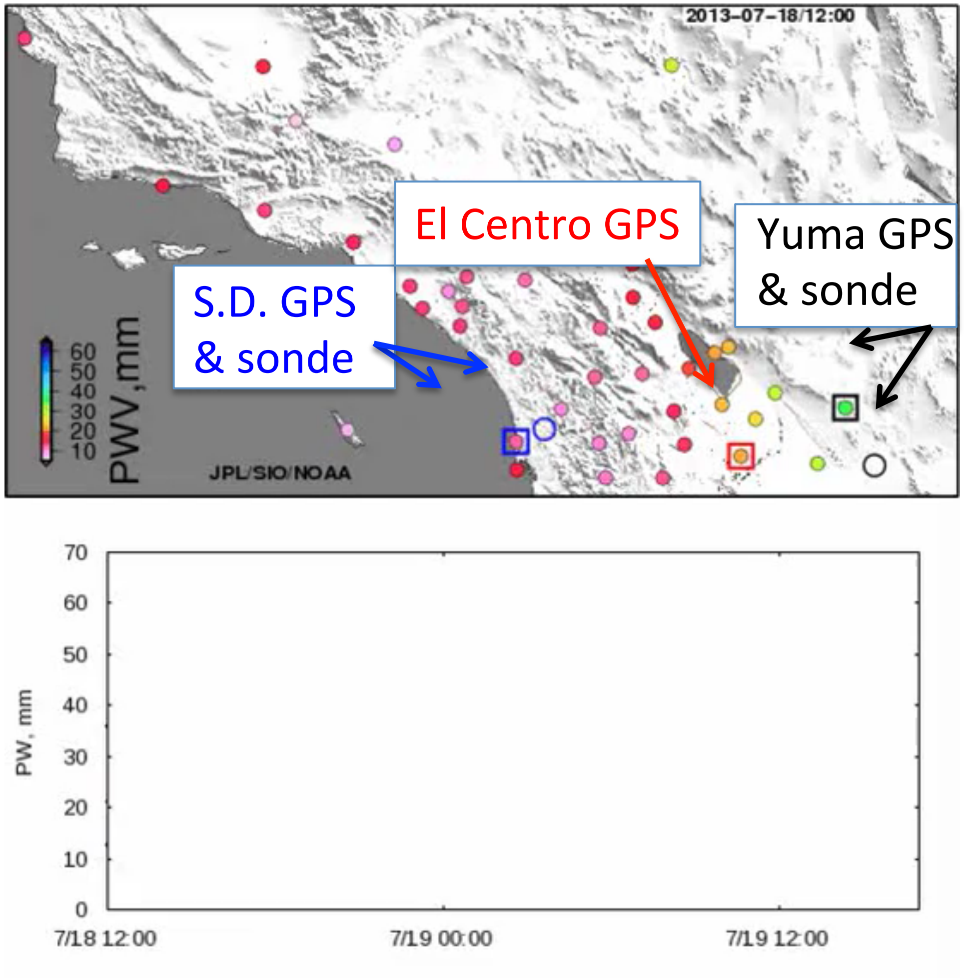
North American Monsoon Event



- NCEP Rapid Refresh model precipitable water with 10m winds on 19 July 2013 illustrating monsoonal moisture surge from the Gulf of California

NCEP – NOAA National Center for Environmental Prediction

July 2013 Monsoon Event: Successful Flash Flood Warning



Forecaster remarks from NWS Weather Forecast Office in San Diego

"Realtime GPS precipitable water estimates were trending higher over eastern portions of the forecast area… a flash flood watch will be needed for Saturday"

"In order to see the character of the precipitable water values between Yuma and San Diego in the absence of a morning Yuma sounding, the GPS meteorology data was utilized."

July 2013 Monsoon Event: Successful Flash Flood Warning

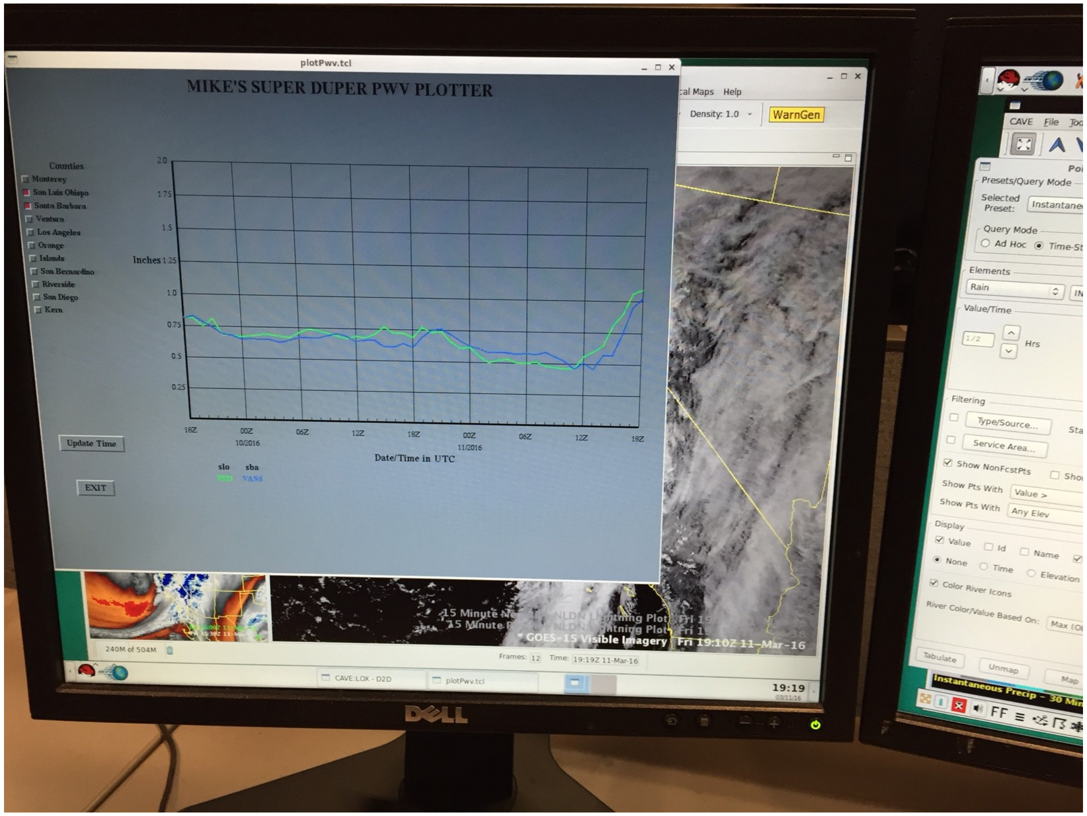
Flooding across Highway 78 in San Diego County, California, 22 Jul 2013.
[Photo credit: NOAA]

Storm reports

"Highway 78 flooded in two locations at Yacqui Pass with 30 vehicles trapped between the two flooded locations. Many large rocks in the roadway."

"Battalion Chief flagged down by the public to report debris moving across the roadway on Sunrise Highway"

Technology infusion:
In-house display of PW data at Los Angeles forecasting office

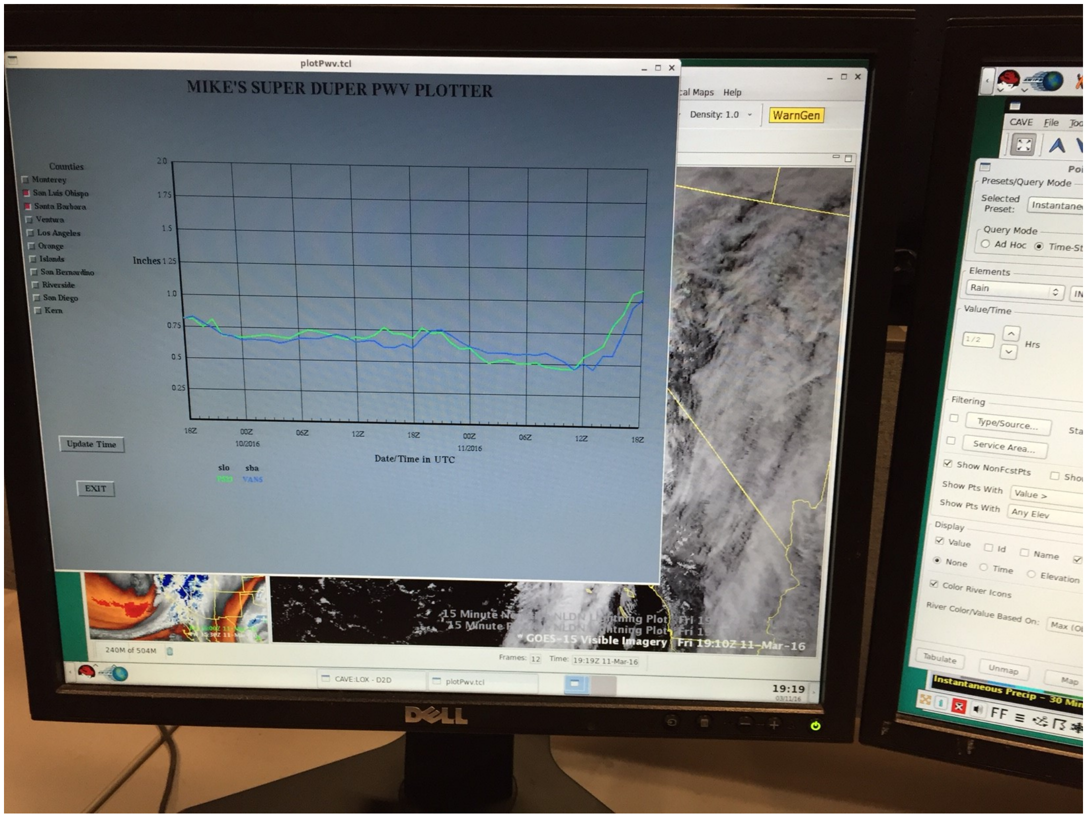


PW plotter developed by Oxnard office to display data from NOAA's MADIS system. This example shows the increase in PW over a six-hour period at two Santa Barbara stations on March 11, 2016 during a rain event.

- Initially provided graphical display of GPS PW data through NOAA ESRL
- Local NWS forecasting offices requested direct access after changes in NOAA ESRL support
- Worked with NWS forecasting offices to implement technology.

ESTO
Earth Science Technology Office

Technology infusion:
In-house display of PW data at Los Angeles forecasting office



PW plotter developed by Oxnard office to display data from NOAA's MADIS system. This example shows the increase in PW over a six-hour period at two Santa Barbara stations on March

- Initially provided graphical display of GPS PW data through NOAA ESRL
- Local NWS forecasting offices requested direct access after changes in NOAA ESRL support
- Worked with NWS forecasting offices to implement technology.

Ultimately, technology infusion and user implementation requires flexibility and adaptation to user's existing systems.

ESTO Earth Science Technology Office

Conclusions

- Developed a power-efficient, low-cost, plug-in Geodetic Module to interface with MEMS accelerometer, met sensors to expand the range of users of GPS Earth observation data.
- Developed real-time analysis of millimeter-level ground motions and precipitable water and algorithms for rapid calculation of high level products.
- Created a real-time autonomous sensor web to transmit and receive information among regional nodes, including directly to users
- Technology transfer to users continues as part of the technology infusion, for decision support and rapid response to earthquakes, tsunamis, severe storms and flash flooding.

Lessons Learned for AIST

- User base was expanded beyond initial demonstration partners
- More demands for direct access drove IT development as time went on.
- Ultimately, technology infusion and new user implementation requires flexibility and adaptation to user's existing systems.